Louisiana State University
LSU Digital Commons

LSU Historical Dissertations and Theses

Graduate School

1972

The Zinc Nutrition and the Growth of Rice as Influenced by Flooding and Applications of Zinc, Lime, and Organic Matter.

Harold Joseph Aymond
Louisiana State University and Agricultural & Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_disstheses

Recommended Citation

Aymond, Harold Joseph, "The Zinc Nutrition and the Growth of Rice as Influenced by Flooding and Applications of Zinc, Lime, and Organic Matter." (1972). *LSU Historical Dissertations and Theses*. 2266.
https://digitalcommons.lsu.edu/gradschool_disstheses/2266

This Dissertation is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Historical Dissertations and Theses by an authorized administrator of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.

INFORMATION TO USERS

This dissertation was produced from a microfilm copy of the original document. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the original submitted.

The following explanation of techniques is provided to help you understand markings or patterns which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting thru an image and duplicating adjacent pages to insure you complete continuity.

2. When an image on the film is obliterated with a large round black mark, it is an indication that the photographer suspected that the copy may have moved during exposure and thus cause a blurred image. You will find a good image of the page in the adjacent frame.

3. When a map, drawing or chart, etc., was part of the material being photographed the photographer followed a definite method in "sectioning" the material. It is customary to begin photoing at the upper left hand corner of a large sheet and to continue photoing from left to right in equal sections with a small overlap. If necessary, sectioning is continued again – beginning below the first row and continuing on until complete.

4. The majority of users indicate that the textual content is of greatest value, however, a somewhat higher quality reproduction could be made from "photographs" if essential to the understanding of the dissertation. Silver prints of "photographs" may be ordered at additional charge by writing the Order Department, giving the catalog number, title, author and specific pages you wish reproduced.

University Microfilms

300 North Zeeb Road
Ann Arbor, Michigan 48106

A Xerox Education Company

73-2939

AYMOND, Harold Joseph, 1941-
THE ZINC NUTRITION AND THE GROWTH OF RICE AS INFLUENCED BY FLOODING AND APPLICATIONS OF ZINC, LIME, AND ORGANIC MATTER.

The Louisiana State University and Agricultural and Mechanical College, Ph.D., 1972
Agronomy

University Microfilms, A XEROX Company, Ann Arbor, Michigan

THIS DISSERTATION HAS BEEN MICROFILMED EXACTLY AS RECEIVED.

THE ZINC NUTRITION AND THE GROWTH OF RICE AS INFLUENCED BY FLOODING AND APPLICATIONS OF ZINC, LIME, AND ORGANIC MATTER

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Agronomy

by
Harold J. Aymond
B. S. University of Southwestern Louisiana, 1964
M. S. Louisiana State University, 1970
August, 1972

PLEASE NOTE:

Some pages may have

indistinct print.

Filmed as received.

University Microfilms, A Xerox Education Company

ACKNOWLEDGMENT

The author wishes to express his sincere appreciation to Dr. J. E. Sedberry, Jr., Professor of Agronomy, Louisiana State University, for his assistance and guidance during the course of this investigation.

The author is indebted to Mr. R. H. Brupbacher, Associate Professor of Agronomy, and Mr. W. P. Bonner, Associate, for their assistance and suggestions made in conduction of the chemical analysis of the soil and plant samples. A special thanks is extended to Mr. S. A. Lytle, Associate Professor of Agronomy, for classifying the soils used in the investigation.

The author is also indebted to Dr. P. E. Schilling, Associate Professor of Experimental Statistics, for his assistance in the statistical analysis and interpretation of the data.

The author is especially grateful to his wife Carolyn, who has most definitely earned the claim to the PhT (putting hubby through) degree.

TABLE OF CONTENTS

LIST OF TABLES

TABLE PAGE

LIST OF FIGURES

FIGURE PAGE

ABSTRACT

Studies were conducted in the greenhouse to determine the effects of flooding and applications of zinc, lime, and organic matter on the production of dry matter and on the concentration and the uptake of zinc, iron, and manganese by rice (Oryza sativa L.) plants grown on selected soils in Louisiana.

Flooding the soils generally resulted in an increase in dry matter production. The increase was attributed to the increased tillering and the increased "availability" of phosphorus and manganese. In most instances, flooding the soil resulted in a reduction in the concentration of zinc in the plants. However, the uptake of zinc was not significantly reduced. Flooding the soil resulted in an increase in the concentration and the uptake of iron and manganese by the rice plants.

The influence of applications of zinc on the production of dry matter depended on the water and the lime treatments, the rice variety, and the soil. The influence of applied zinc on dry matter production varied from a significant increase to a significant decrease. Where the application of zinc significantly reduced dry matter production, the reduction was attributed to such factors as the reduction in the manganese:iron ratio in the plants, zinc-induced phosphorus deficiency, and zinc-induced iron toxicity.

The 0.1 N HCl extractable zinc content of the soil was not related to either the concentration or the uptake of zinc by rice plants. This suggested that the use of 0.1 N HCl extractable zinc does not provide a reliable index of the "availability" of zinc to rice plants grown on flooded soils.

The application of zinc resulted in an increase in the concentration and the uptake of zinc by rice plants. However, not all of the increases were statistically significant. The influence of applications of zinc on the concentration and uptake of iron and manganese varied from a significant increase to a significant decrease. The data indicated that zinc-iron and zinc-manganese interactions occurred. The nature of the interactions depended on factors such as the water and lime treatments, the rice variety, and the soil.

The application of lime resulted in a decrease in dry matter production, the concentration, and the uptake of zinc. Under nonflooded conditions, the application of lime decreased the concentration of iron in the rice plants. Under flooded conditions, the application of lime increased the concentration of iron in the plants. Under both flooded and nonflooded conditions, the application of lime reduced the uptake of iron by the plants. The adjustment of the pH of a Patoutville silt loam from 4.6 to 5.5 and 6.0 with the application of 1 and 2 tons of lime per acre resulted in a progressive decrease in the concentration and the uptake of manganese. Increasing the pH to 6.5 and 6.9 with the application of 3 and 4 tons of lime resulted in an increase in the concentration and the uptake of manganese.

The application of different forms of organic matter resulted in a significant decrease in dry matter production. The concentration of zinc in the rice plants was not significantly affected by the application of organic matter. The application of rice straw and cellulose significantly reduced the uptake of zinc, the application of soybean leaves did not. The concentration and uptake of iron were reduced by the application of organic matter. However, the reduction in the concentration of iron was not statistically significant when cellulose was applied. The concentration and uptake of manganese were significantly reduced by the application of soybean leaves and rice straw. The concentration, but not the uptake, was significantly increased by the application of cellulose.

INTRODUCTION

The essentiality of zinc for the growth and development of plants has been known for some time. Sommer and Lipman (1926) demonstrated the requirement of zinc by barley, sunflower, beans, and several other crops. Their research led to the acceptance of zinc as an essential plant nutrient element.

Zinc deficiency was first described and corrected in Louisiana in 1932 by Dr. A. O. Alben, USDA Pecan Station, Robson, Louisiana. Zinc deficiencies have been reported in areas throughout the world and zinc is probably the most commonly deficient of all the micronutrient elements (Kline, 1965). Until recently, the specific use of zinc as a fertilizer element was restricted primarily to fruit and nut trees. However, a great deal of attention has been drawn to the use of zinc fertilizer in the production of field crops. The increased interest in the zinc status of soils and the zinc nutrition of agronomic crops has been brought about by several factors such as lower amounts of zinc occurring in fertilizers due to the increased usage of higher analysis fertilizers, greater crop removal of zinc due to increased crop yields, and increased knowledge and refinement of analytical methods and techniques used in the detection of relatively small quantities of zinc.

Refinement and improvement of analytical techniques has perhaps been responsible for most of the stimulated interest in identifying and solving problems related to zinc deficiencies. The use of new and improved techniques has spawned a great deal of research in the past decade and an immense amount of knowledge has been acquired and disseminated. However, many questions concerning zinc deficiency and its correction remain unanswered.

The primary causes of zinc deficiency are low solubility of indigenous soil zinc and inherently low content of total zinc in the soil. The low solubility or availability of zinc is probably of greater significance than is the total amount of zinc in the soil. Therefore, any factor or practice which tends to reduce the solubility of zinc may result in the occurrence of zinc deficiency.

Preliminary research conducted by Sedberry et al. (1971) indicated that under certain conditions, rice (_Oryza sativa_ L.) grown on the Prairie soils in Louisiana responded to applications of zinc. Since only a limited amount of data on factors affecting the zinc nutrition of rice grown on soils in Louisiana is available, this investigation was initiated with the following objectives: 1) to determine the influence of soil applications of zinc on the growth and on the concentration and the uptake of zinc, iron, and manganese by rice plants grown on selected soils in Louisiana; 2) to determine the influence of flooding and the effects of applications of lime and organic matter on the growth and on the concentration and the uptake of zinc, iron, and manganese by rice plants; 3) to study possible zinc-iron and zinc-manganese interactions and the influence of these interactions on the zinc nutrition of rice grown on selected soils in Louisiana.

REVIEW OF LITERATURE

The total supply of plant nutrient elements in the soil and their "availability" to the plant are the two general factors that govern the ability of a soil to provide sufficient nutrients to a growing plant. Deficiencies may be a result of a naturally low fertility level and/or a result of a fixation process which retains or fixes nutrients in a form that cannot be utilized by the plant. Although there are some soils which have such a limited supply of zinc that zinc deficiencies would occur regardless of the availability, the major cause of zinc deficiencies appears to be one of plant availability and not total soil content.

Factors Affecting the Availability of Zinc

There are many soil factors associated with the deficiency of zinc in plants. One of the first factors to be correlated with zinc deficiency was soil reaction (pH). As early as 1938, a definite correlation between the hydrogen-ion concentration and the availability of zinc in the soil was demonstrated by Lott (1938). His results indicated that as the acidity of the soil increased, there was a subsequent increase in the solubility of zinc. Epstein and Stout (1951) found that the amount of zinc absorbed by tomatoes from bentonite suspensions was related to the suspension pH. The lower the pH, the greater the zinc uptake. As the pH increased, insoluble zinc hydroxide was thought to be formed (Seatz and Jurinak, 1957). The results obtained by Seatz and Jurinak (1957) indicated that zinc availability was at a minimum when the soil pH range was 5.5 to 7.0. Camp (1945) concluded that the critical range of zinc availability in the soil was between the range of pH 5.5 to 6.5. Zinc, like several other metals, forms a hydroxide and has the ability to act as a base or a weak acid depending on the pH of the environment. Camp (1945) suggested that in alkaline soils the formation of a negatively charged zincate complex may be a significant factor in reducing the availability of zinc.

In the case of rice grown under submerged soil conditions, the effect of pH on the availability of zinc becomes increasingly important. It has been established that the pH of a soil tends towards neutrality under submerged conditions (Ponnamperuma, 1964). This change in the pH of the soil could influence zinc availability. It appears probable that due to the increase in the pH, the level of available zinc in a moderately acid soil would decrease when the soil is submerged. Experiments conducted by investigators at the International Rice Research Institute (1969) demonstrated that the submergence of an acid soil reduced the concentration of zinc in rice plants by as much as 75%. They concluded that the decrease in the zinc concentration in the plants was due to a reduction in the availability of zinc in the soil, as a result of the increase in the pH after the soil was submerged.

Yoshida and Tanaka (1969) found that the zinc deficiency of rice plants was associated with high pH and/or calcareous soils. Their results showed that the zinc content of the rice plants was not related to total soil zinc, but was closely related to soil pH. Khan (1969) demonstrated that the addition of calcium carbonate to the soil induced zinc deficiency of rice plants grown under both upland and lowland conditions. He attributed the reduced availability of zinc to the change in pH brought about by addition of the calcium carbonate.

There are numerous reports in the literature which discuss the influence of additions of lime on the availability of zinc. Wear (1956) studied the effect of soil pH and calcium on the uptake of zinc. He found that additions of calcium carbonate decreased the zinc content of sorghum. Sodium carbonate had the same effect. The decrease in zinc uptake was associated with the change in pH brought about by the addition of the two materials. The addition of calcium sulfate to the soil resulted in a slight increase in the uptake of zinc by the sorghum plants. Wear interpreted this to mean that the reduction in the uptake of zinc by the plants following the addition of the liming materials was due to the effect on pH and not a calcium effect. Brown and Jurinak (1964) also studied the influence of lime on the availability of zinc. Their results indicated the reduction in the availability of zinc was due to the effect of lime on the pH of the soil and not a calcium effect.

Rogers and Chik-Hwa Wu (1948) found that the application of lime reduced the zinc content of oats. Seatz (1960) and Seatz, Sterges, and Kramer (1959) also reported that additions of lime decreased the concentration and the uptake of zinc by various plants. Gall and Barnette

(1940) reported using lime to reduce the toxicity of relatively high levels of zinc in the soil.

Navrot and Ravikovitch (1969) found an inverse relationship between the absorption of native zinc by tomatoes and the calcium carbonate level in soils originating from calcareous parent material. They found that the uptake of added zinc was affected by the particle size of calcium carbonate. Increasing amounts of calcium carbonate particles of 2 microns or less in size, tended to progressively reduce the uptake of zinc. They reported that the amount of zinc extracted from calcareous soils was governed by the level of calcium carbonate less than 2 microns in size present in the soil.

Through its influence on soil pH, the type of nitrogen carrier used may have an effect on pla uptake of zinc. Viets, Boawn, and Crawford (1957) and Boawn et al. (1960) studied the effect of nitrogen and types of nitrogen carrier on the uptake of zinc by plants. Their research revealed that nitrogen applications generally increased the uptake of both native and applied zinc. The effect depended upon the change in soil pH brought about by the nitrogen carrier. The use of ammonium sulfate alone, resulted in a greater uptake of zinc than did the use of sodium nitrate combined with the addition of four pounds per acre of zinc sulfate. Where the nitrogen source effect was observed, it was found to be closely correlated with changes in soil pH caused by the addition of the nitrogen source. Viets et al. (1957) postulated that nitrogen increased uptake of zinc by plants either by promoting more extensive and intensive root development and/or through an acidifying effect on the soil.

Research conducted by investigators at the International Rice Research Institute (1970) demonstrated that "physiologically acid" nitrogeneous fertilizers such as ammonium chloride and ammonium sulfate, may improve the uptake of zinc by rice plants grown on calcareous soils low in zinc. They found that urea applied to rice plants grown on a calcareous soil low in zinc caused severe symptoms of zinc deficiency to develop. Plants supplied with ammonium sulfate showed only slight symptoms of zinc deficiency, while plants supplied with ammonium chloride, as the nitrogen source, did not show any symptoms of zinc deficiency.

A review of research by Mortensen (1963) has shown that soil organic matter forms complexes with metals by ion exchange, surface reaction and absorption, and chelation reaction mechanisms. Randhawa and Broadbent (1965) found that the amount of zinc complexed by humic acid was influenced by pH. As the pH increased, the amount of zinc complexed was increased.

Under field conditions, zinc deficiencies have been observed where organic matter was considered to be high. In Utah, zinc deficient orchards usually have been fertilized for many years with liberal applications of farm manure (Thorne, 1957). Zinc deficiencies have been observed in sites that formerly were corrals or barnyards. These deficiencies were thought to be closely associated with the relatively high amounts of organic matter present (Chandler, 1937).

According to DeNumbrum and Jackson (1956), peat may hold zinc and copper by a chelation type of reaction. Baughman (1965) has stated that zinc retained by organic matter was chelated and complexed. His results indicated that chelation and complexing of zinc by organic matter may be a significant factor in reducing zinc availability in soils.

Millikan (1942) found that cereals planted on soils that were recently plowed from stubble exhibited more zinc deficiency symptoms than did those planted on soils that were allowed to fallow. Shaw et al. (1954), working with various soils, reported that applying four tons of dry organic matter per acre significantly reduced plant uptake of ^{65}Zn.

Some workers have concluded, however, that the amount of zinc associated with the soil organic fraction is small and probably does not influence the availability of zinc to plants to any great extent. Hubbard, as reported by DeRemer and Smith (1964), failed to obtain significant releases of zinc in several soils by burning the organic matter or oxidizing it with hydrogen peroxide. Since Tucker and Kurtz (1955) recovered such small amounts of zinc that were released when the organic matter in several soils was destroyed with hydrogen peroxide, they concluded that only a small portion of soil zinc occurred in the organic form.

Research conducted by investigators at the International Rice Research Institute (1969) showed that zinc deficiencies in rice plants could be induced by the addition of organic matter. They found that the addition of cellulose, as well as the addition of soybean leaves and rice straw, resulted in the appearance of zinc deficiency symptoms, decreased growth, and lower zinc content of rice plants. The decrease in growth was attributed to the reduced zinc content of the plants. Additional research conducted by investigators at the International Rice Research Institute (1970) indicated that the addition of cellulose to the soil did not significantly reduce the zinc concentration in the soil solution. It was therefore concluded that the aggravation of zinc deficiency induced by the addition of cellulose was not due to a change in the concentration of zinc in the soil solution, but to some other factor retarding the absorption of zinc by rice plants.

Zinc may be somewhat immobilized in the soil by absorption on surfaces of clay and humus. Therefore, the extensiveness of root development may be of more importance in the uptake of zinc than for the uptake of more mobile nutrient elements. Since temperature may affect root development, it appears probable that soil temperature may have at least an indirect effect on the uptake of zinc, especially in young seedlings. This is borne out by the fact that the appearance of zinc deficiency symptoms in newly seeded crops such as corn or beans are more frequently observed in cold wet springs than in warm ones. This appears to be a result of the effect of temperature, as the plant apparently "grows out" of the deficiency symptoms as the temperature increases and the plants develop (Ellis, Davis, and thurlow, 1964).

Although not much research has been carried out on the effect of temperature on zinc uptake, there is evidence that temperature does exert an influence. Ellis et al. (1964) observed a decrease in the zinc concentration in plant tissue and the total uptake of zinc by corn plants when the soil temperature was decreased from 24C to 13C. Martin, McLean, and Quick (1965) demonstrated that for a soil containing 0.9 ppm dithizone extractable zinc, it was possible to induce zinc deficiencies in tomatoes with additions of phosphorus when the soil temperature was kept at 10C and 16C. Phosphorus-induced zinc deficiencies did not occur when the soil temperature was increased to 21C and 27C. Ganiron et al. (1969) reported that corn seedlings grown at lower temperatures had about equal concentrations of zinc in the shoots and roots. Ganiron et al. (1969) interpreted this to mean that temperature affected the availability of soil zinc rather than influencing the uptake or translocation of zinc. Sharma et al. (1968) reported that a progressive decrease in soil temperature from 30 to 22.5 and to 15C gave a progressive decrease in the zinc uptake and dry matter of rice plants. They also noted that the response to zinc decreased with increasing soil temperature. They observed that at 15C, the application of zinc increased the concentration of zinc in the roots, but did not significantly increase the concentration of zinc in the shoots indicating that temperature had some effect on the translocation of zinc in rice plants. This is in direct opposition to the conclusion drawn by Ganiron et al. (1969) that temperature did not influence the translocation of zinc.

Bauer and Lindsay (1965) studied the effect of soil temperature on the availability of native soil zinc. They incubated a zinc deficient Weld loam soil for periods of 0, 1, 3, and 6 weeks at temperatures of 5, 17, 31, and 43C. The soil was treated with 0 and 0.75 ppm of zinc sulfate immediately prior to planting two-week-old corn plants. The corn plants were allowed to exploit the previously incubated soil for a two-week period. Both yield of dry matter and uptake of zinc were greater from the soil that had been incubated at 43C for 1 and 3 weeks than any other treatments. The addition of zinc showed that zinc was a limiting factor in growth of the corn plants grown in the soil that had been incubated at the lower temperatures.

Bauer and Lindsay (1965) offered several suggestions as to the mechanism of the temperature effect on the availability of zinc: (1) release of available quantities of zinc at higher temperatures may suggest that the microbial population is involved, (2) a non-biological temperature dependent mechanism may be responsible for mineralization of zinc containing compounds, (3) there may be a release of natural chelating agents during the decomposition of organic residues at higher temperatures, and (4) the mechanism may be due to the effect of increased carbon dioxide pressure which may cause an increase in the hydrogen ion activity.

A great deal of research has been conducted on the influence of phosphorus on the uptake and utilization of zinc by plants. Excessive amounts of phosphorus in the soil have been associated with low zinc availability in many regions of the world. Chapman, Vanselow, and Liebig (1937) reported that high concentrations of phosphorus induced zinc deficiency symptoms in orange seedlings grown in nutrient solutions. However, Bingham (1963) stated that he could not induce zinc deficiency of seedlings grown in sand culture with as much as 100 ppm of phosphorus and only 0.05 ppm of zinc in the nutrient solution.

Burleson, Dacus, and Gerard (1961) reported that severe zinc deficiency of beans could be induced by application of large amounts of phosphorus. They also reported that when both zinc and phosphorus were applied, the uptake of both zinc and phosphorus was reduced. Martin et al. (1965) also noted that phosphorus applications reduced the zinc concentration in the leaf tissue of potato plants, while the application of zinc tended to decrease the concentration of phosphorus in the leaves. Ellis et al. (1964) reported that in most of their experiments, a negative correlation was obtained between zinc and phosphorus concentrations in plant tissue. However, the results of research conducted by Warnock (1970) indicated that even though applied phosphorus reduced the concentration of zinc in corn plants, the total uptake per plant was not reduced.

According to Ward et al. (1962), the occurrence of zinc deficiencies was greater on calcareous soils that were inherently high in phosphorus and low in soluble zinc. They stated that, the more effectively phosphorus was utilized by the crop, the more severe was the reduction in the uptake and utilization of zinc. They suggested that low rates of phosphorus rather than large, infrequent applications would more likely result in less damaging effects on zinc uptake. Melton, Ellis, and Doll (1970) also noted that heavy applications of phosphorus generally induced greater zinc deficiency on soils that were neutral to alkaline in reaction.

There have been many theories as to the possible mechanism of phosphorus-zinc interactions. Results from greenhouse experiments conducted by Burleson et al. (1961) suggested a possibility of phosphorus-zinc antagonism within plant roots. Stukenholtz et al. (1966) found that in corn, the translocation of zinc from the roots to the shoots was inhibited by high phosphorus concentrations which resulted in a reduction of the zinc concentration of nodal and internodal tissues. They suggested that the depressive action of phosphorus on zinc uptake appeared to be physiological and not a result of chemical inactivation of zinc by phosphorus in the soil. Ellis et al. (1964) presented data which supported the hypothesis that the phosphorus-zinc interaction occurred either at the root surface or within the roots of corn plants. Ward et al. (1962) reported that the damaging effect of phosphorus on zinc utilization was largely physiological in nature and probably a plant root cell absorption phenomenon, and not an external zinc phosphate precipitation.

Research by Paulsen and Rotini (1968) indicated that the depressing effect of phosphorus on zinc originated in the roots and influenced the translocation of zinc to the upper plant parts. Pauli, Ellis, and Moses (1968) presented evidence that a high phosphorus-zinc ratio increased the water extractable zinc in the soil. They concluded that the phosphorus-zinc interaction phenomenon occurred in the roots rather than in the soil. Burleson and Page (1967), using flax as an indicator plant, concluded that the phosphorus-zinc interaction occurred at the root surfaces or within the plant. They suggested that phosphorus and zinc interacted, within the root, in such a manner that reduced their mobility and/or solubility.

The effect of flooding the soil on the zinc concentration in rice plants is well documented (Yoshida and Tanaka, 1969; Senewiratne and Mikkelsen, 1961; Kahn, 1969). Cherian, Paulsen, and Murphy (1968) reported a significant decrease in the zinc concentration of rice plants grown under flooded conditions. Chaudhry and McLean (1963) also reported obtaining lower zinc concentrations in rice plants grown under flooded conditions. Research by investigators at the International Rice Research Institute (1969) indicated that both the concentration and the uptake of zinc by rice plants grown under flooded conditions on an acid soil was reduced. The zinc concentration, but not the total uptake, was reduced when the plants were grown under flooded conditions on a calcareous soil. They found that when the acid soil was flooded, the zinc content of the rice shoots decreased sharply. They suggested that this may have been a result of the decreased availability of zinc due to the increase in the pH of the soil when it was flooded. Flooding the calcareous soil resulted in a decrease in the zinc concentration in the rice plants, even though the pH of the soil was expected to be lowered after flooding of the soil. They suggested that the decrease in the zinc concentration in the rice plants could be partially explained by the increased growth of the plants under flooded conditions. Further research by investigators at the International Rice Research Institute (1970) demonstrated that the zinc concentration in the soil solution decreased sharply upon flooding, and tended to decrease to a fairly constant level to about 0.01 ppm of zinc in solution. They observed that the addition of cellulose to the soil did not decrease the zinc concentration in the soil solution. However, the addition of cellulose tended to aggravate zinc deficiencies of rice plants, although the plants appeared to recover from these symptoms some time later. They suggested that some factor or factors must retard the absorption of zinc by the rice plant immediately after the initial flooding of the soil and that the effect of these factors is removed or somehow counterbalanced a few weeks after flooding of the soil.

Zinc-Iron Interaction in Plants

There is ample evidence in the literature that iron-zinc interactions occur in some plants. Lingle, Tiffin, and Brown (1963), using radioactive isotopes of zinc and iron, reported that zinc inhibited the accumulation of iron in the exudate of soybean plants. They observed that at low concentrations, heavy metal cations such as manganese and copper stimulated iron transport into the xylem of decapitated soybean plants. They found that at low concentrations, zinc inhibited iron transport into the xylem of soybean plants. Tiffin (1967) demonstrated that zinc had an inhibitory effect on iron accumulation and transport in tomato plants.

Rosell and Ulrich (1964) reported that the leaves of zinc-deficient sugar beet plants contained an unusually high concentration of iron. The application of zinc resulted in as much as an 80% reduction in the iron concentration in the leaves. Warnock (1970) reported a relationship between phosphorus-induced zinc deficiency in corn and the concentration and mobility of iron within the plant. He observed that zinc-deficient corn plants accumulated a large excess of iron. He suggested that the excessive iron concentration was associated with zinc deficiency in the plant and not with the level of iron in the soil solution. Adriano, Paulsen, and Murphy (1971) reported that iron and zinc were mutually antagonistic in corn seedlings. They found that the growth of corn seedlings was depressed at both low and high iron levels. They suggested that iron deficiency at the low level of iron retarded growth, whereas at the high iron level zinc deficiency was accentuated.

Ambler, Brown, and Gauch (1970) and Brown, Holmes, and Tiffin (1961) reported that the absorption of iron by soybeans is related to the ability of the roots to reduce Fe^{3+} to Fe^{2+}. Chaney, Brown, and Tiffin (1972) indicated that the reduction of iron appeared to be obligatory before iron could be absorbed by the soybean root. They concluded that the inhibitory effect of zinc on iron absorption was related to the reduction of Fe^{3+} to Fe^{2+}

Zinc-Manganese Interaction in Plants

There appears to be some disagreement in the literature concerning zinc-manganese interactions in plants. Schmid, Haag, and Epstein (1965) reported that manganese had essentially no effect on the absorption of zinc by barley roots. Bowen (1969) reported that manganese and zinc did not compete for similar absorption sites in sugar cane. He concluded that manganese and zinc were not antagonistic and the absorption of one was not affected by the other. However, Maas, Moore, and Mason (1968) reported that zinc reduced the absorption of manganese by barley roots. They concluded that the interaction of manganese and zinc occurred at some point other than the actual transport or absorption sites.

Adriano and Murphy (1970), in studying phosphorus-zinc relationships, observed that zinc had an influence on the manganese concentration in corn plants. They reported that high levels of zinc tended to depress the manganese content of the corn plants, whereas high levels of phosphorus tended to enhance manganese concentration and uptake. They suggested that the effect of zinc on manganese uptake may have been produced by a reduced phosphorus concentration in the plant or by a direct antagonism between zinc and manganese absorption.

Investigators at the International Rice Research Institute (1969) reported that an interaction between zinc and manganese existed in rice plants grown in culture solutions. They observed that rice plants showing zinc deficiency symptoms tended to accumulate much more manganese than the plants showing no apparent symptoms of zinc deficiency. The manganese concentration in rice plants grown in culture solutions containing 0.0001 ppm of zinc was more than five times greater than that of plants grown in culture solutions containing 0.01 ppm of zinc. The addition of 0.01 ppm of zinc to the culture solution resulted in an increase of only 2 ppm in the concentration of zinc in the plants, whereas the manganese concentration of the plant was reduced by more than 2000 ppm.

Critical Level of Zinc in Plant Tissue

According to Chapman (1966), zinc deficiencies have been noted in a wide variety of plants when the level of zinc was less than 25 ppm in the dry matter. Seatz and Jurinak (1957) reported that the concentration of zinc in plants varied with the amount of available zinc in the soil, the kind of plant, the plant part sampled, and the stage of growth of the plant. There is a considerable amount of evidence that zinc readily accumulates in the leaves of certain plants. However, in the case of rice, zinc may be fairly well distributed throughout the shoot portions of the plant. Research by investigators at the International Rice Research Institute (1970) demonstrated that the zinc concentration in rice leaves did not vary greatly from one leaf to another, although the younger leaves tended to have a higher zinc concentration than older leaves when the rice plants were grown in mediums containing relatively high concentrations of zinc. Based on this evidence, they concluded that analysis of the whole rice shoot provided approximately the same information about the zinc status of the rice plant as did the analysis of particular leaves. For convenience and ease in sample collecting, they suggested that the whole shoot be used for diagnosis of zinc deficiency. Their results showed that if the zinc content of the shoot of the rice plant at an early stage of growth is less than 10 to 15 ppm, zinc deficiency is likely to occur. This is in agreement with the conclusion drawn by Ishizuka and Tanaka as reported by Yamasaki (1964). Research conducted in Louisiana by Sedberry et al. (1971) indicated that a yield response to applied zinc may be obtained when the concentration of zinc in the leaves of rice plants, sampled when the panicles were 2 mm long, was less than 15 ppm.

Critical Level of Zinc in the Soil

Many researchers have attempted, through soil analysis, to determine the ability of a soil to supply zinc to a plant. Various extracting solutions have been utilized to ascertain the zinc supplying power of soils. Martens and Chesters (1967) reported a significant correlation between the zinc extracted from soils by 0.2 M magnesium sulfate, 0.1 N hydrochloric acid, or dithizone and uptake of soil zinc by corn plants. Brown and Krantz (1961), using dithizone as an extractant, found 0.5 ppm of zinc to be a critical level below which a zinc response might be expected for crops sensitive to low availability of zinc. Wear (1959) reported that corn responded to applications of zinc when the pH of the soil was above 5.9 and the dithizone extractable zinc was less than 0.90 ppm. Shaw and Dean (1952) reported that many crops exhibited zinc deficiency symptoms when the level of dithizone extractable zinc was less than 1.0 ppm in soils with pH values of 7.0 or greater.

The use of 0.1 N hydrochloric acid as an extractant for estimating soil zinc availability is widespread. Wear and Sommer (1948) found a good correlation between acid extractable zinc and the presence or absence of deficiency symptoms in corn plants. They observed that zinc deficiency symptoms occurred when the acid extractable zinc content of the soil ranged from 0.50 to 0.90 ppm. Viets et al. (1953) found that the level of acid extractable zinc in soils where various crops appeared to be deficient in zinc was from 0.8 to 1.3 ppm. The level of acid extractable zinc in soils where crops did not appear to be deficient in zinc was greater than 1.3 ppm. Kanehiro and Sherman (1967) also reported a good correlation between zinc-deficient plants and acid extractable zinc. Sedberry et al. (1971) suggested that the critical level of zinc for rice grown on Prairie soils in Louisiana was 1.2 ppm or less of zinc.

Trierweiler and Lindsay,as reported by Engler (1969), have successfully used ethylenediamine (EDTA) as a soil extractant. They found that a response to either zinc or zinc and phosphorus was obtained when the level of EDTA extractable zinc was less than 1.4 ppm. No response was obtained when the extractable zinc was above this level. Engler (1969) reported that the Colorado State University Soil Testing Laboratory used diethylenetriamine penta-acetic acid (DPTA) as an extractant for diagnosing zinc-deficient soils. They noted that 0.8 ppm of zinc extracted with DPTA was the critical zinc level in the soil for corn production. When more than 0.8 ppm of zinc was extracted by this method, corn did not respond to additions of zinc.

MATERIALS AND METHODS

Studies were conducted in the greenhouse and in the laboratory to determine the effects of flooding and applications of zinc, lime, and organic matter on the production of dry matter and on the concentration and uptake of zinc, iron, and manganese by rice (Oryza sativa L.) plants.

A 400 kg bulk sample of soil was collected from each of 29 locations in Louisiana. For the purpose of identification and convenience in reporting, each sample was arbitrarily assigned a number from 1 to 29. The soil types, subgroups, and locations of the soils used in the studies are presented in Table 1. The soils were air-dried, pulverized, mixed, and sieved through a 6 mm plastic screen. A representative sample of soil was taken from each bulk sample for chemical analysis. The bulk samples were then stored in plastic-lined containers.

The dilute acid extractable phosphorus, potassium, calcium, and magnesium contents of the soil samples were determined according to the methods described by Brupbacher, Bonner and Sedberry (1968). Phosphorus was extracted with a 0.10 N HCl solution containing 0.03 N ammonium fluoride at a soil to solution ratio of 1:20. The concentration of P was determined on an aliquot of the soil extract after a blue color was developed upon adding a solution containing ammonium molybdate, sulphuric acid and boric acid, and a solution containing stannous chloride. The intensity of the color developed was measured on

Table 1. The soil type, subgroup and location of soil samples used in the greenhouse and laboratory investigations.

Sample Number	Soil Type 1/	Subgroup	Location (Parish)
- - - - - - - - - - -Mississippi River Alluvial Soils - - - - - - - - -			
1	Mhoon sicl	Fluventic Haplaquepts	Plaquemines
- - - - - -Alluvial Soils of the Ouachita & Arkansas Rivers - - - - -			
2	Gallion sil	Typic Hapludalfs	Grant
3	Hebert sil	Aeric Ochraqualfs	Caldwell
4	Hebert sil	Aeric Ochraqualfs	Morehouse
5	Hebert sil	Aeric Ochraqualfs	St. Landry
- - - - - - - - - - -Alluvial Soils of the Red River- - - - - - - - - -			
6	Pulaski vfsl	Typic Ustifluvents	St. Landry
7	Norwood sil	Typic Udifluvents	Bossier
8	Norwood sil	Typic Udifluvents	Rapides
9	Norwood sil	Typic Udifluvents	Rapides
10	Yahola vfsl	Typic Ustifluvents	Avoyelles
11	Yahola vfsl	Typic Ustifluvents	Rapides
- - - - - - - - - - -Coastal Plains & Flatwoods Soils - - - - - - - - -			
12	Bowie fsl	Plinthic Paleudults	Vernon
13	Shubuta fsl	Typic Paleudults	DeSoto
14	Ruston fsl	Typic Paleudults	Washington
- - - - - - - - - - - Soils of the Coastal Prairies - - - - - - - - - -			
15	Acadia sil	Aeric Ochraqualfs	Evangeline
16	Acadia sil	Aeric Ochraqualfs	Acadia
17	Crowley sil	Typic Albaqualfs	Acadia
18	Crowley sil	Typic Albaqualfs	Acadia
19	Crowley sil	Typic Albaqualfs	Acadia
20	Crowley sil	Typic Albaqualfs	Acadia
21	Crowley sil	Typic Albaqualfs	Acadia
22	Morey sil	Typic Argiaquolls	Calcasieu
23	Mowata sil	Typic Glossaqualfs	Vermilion
24	Bernard cl	Vertic Argiaquolls	Cameron

(Continued)

Table 1 (Continued).

Sample Number	Soil Type 1/	Subgroup	Location (Parish)
- - - - - - -Mississippi Terraces & Loessial Hills Soils- - - - - - -			
25	Patoutville sil	Aeric Ocharqualfs	Acadia
26	Patoutville sil	Aeric Ocharqualfs	St. Landry
27	Patoutville sil	Aeric Ocharqualfs	Vermilion
28	Jeanerette sil	Typic Argiaquolls	Acadia
29	Jeanerette sil	Typic Argiaquolls	Acadia

1/ Soils classified by S. A. Lytle, Associate Professor, Louisiana Agricultural Experiment Station.

a Bausch and Lomb Spectrophotometer. Potassium, calcium, and magnesium were extracted with a 0.10 N HCl solution at a soil to extracting solution ratio of 1:20 and determined using a Perkin-Elmer Model 303 atomic absorption spectophotometer.

A Leeds and Northrup glass electrode pH meter was used to measure the soil reaction. A slurry of soil and distilled water at a soil to solution ratio of approximately 1:1 was employed. The organic matter content of the soil samples was determined by the chromic acid method proposed by Walkley and Black (1934).

A procedure described by Jackson (1958) using 1 N ammonium acetate, adjusted to pH 7.0, was employed for the determination of cation exchange capacity. Ten percent potassium chloride was used to displace the ammonium ions absorbed by the exchange complex. The exchangeable soil cations were determined using a Perkin-Elmer Model 303 Atomic Absorption Spectrophotometer. The percent base saturation was calculated by dividing the sum of the soil cations by the cation exchange capacity and multiplying by 100. The extractable phosphorus, potassium, calcium, and magnesium contents, the pH, the organic matter content, the cation exchange capacity, and the base saturation of the soils used in the investigations are presented in Table 2.

The contents of zinc, iron, and manganese in each soil were determined. The dilute acid extractable zinc content of the soil was determined by extracting 5 grams of soil with 0.10 N HCl at a soil to solution ratio of 1:10. The soil and extracting solution were agitated for 15 minutes on a mechanical shaker. Iron and manganese were

Table 2. Certain chemical properties of soil samples used in the greenhouse and laboratory investigations.

Sample Number	Soil Type	Extractable Nutrients P	K	Ca	Mg	pH	Organic Matter	CEC pH 7.0	Base saturation
		- - - - - -ppm- - - - - - -					%	meq/100g	%
- - - Mississippi River Alluvial Soils - - -									
1	Mhoon sicl	337	257	2305	692	6.6	1.27	26.1	66.7
- - - Alluvial Soils of the Ouachita & Arkansas Rivers - - -									
2	Gallion sil	183	184	310	93	5.7	0.60	4.3	59.3
3	Hebert sil	200	116	205	117	4.5	0.73	7.3	40.5
4	Hebert sil	104	115	572	146	6.6	0.83	5.1	63.0
5	Hebert sil	72	125	749	249	5.6	1.20	13.3	47.6
- - - Alluvial Soils of the Red River- - -									
6	Pulaski vfsl	38	45	180	80	6.1	0.57	4.5	37.9
7	Norwood sil	161	131	4000	1000	7.4	0.68	13.9	86.6
8	Norwood sil	171	69	876	300	6.6	1.17	9.6	69.7
9	Norwood sil	159	72	4000	1000	7.8	0.34	10.1	100.0
10	Yahola vfsl	205	57	784	208	7.1	0.73	8.2	60.3
11	Yahola vfsl	137	95	340	97	6.1	0.60	6.6	50.4
- - - Coastal Plains & Flatwoods Soils - - -									
12	Bowie fsl	103	39	342	168	5.7	1.48	3.1	52.7
13	Shubuta fsl	83	140	213	93	6.1	0.83	3.9	51.0
14	Ruston fsl	24	51	306	160	5.5	1.20	5.7	56.4

(Continued)

Table 2 (Continued).

Sample Number	Soil Type	Extractable Nutrients P	K	Ca	Mg	pH	Organic Matter	pH 7.0	Base saturation
		------ ppm-	-----				%	meq/100g	%
------------------	-Soils of the Coastal Prairies-	------------------							
15	Acadia sil	39	44	986	90	7.2	0.49	6.8	47.5
16	Acadia sil	34	110	367	138	4.8	1.51	9.3	34.7
17	Crowley sil	34	46	804	251	6.3	0.62	10.2	67.7
18	Crowley sil	30	49	841	263	6.4	0.88	9.4	76.8
19	Crowley sil	24	59	938	290	6.8	1.69	11.7	67.0
20	Crowley sil	20	50	760	251	6.4	1.22	9.4	62.4
21	Crowley sil	20	50	1320	401	7.5	0.73	11.9	72.4
22	Morey sil	55	53	998	164	5.6	1.20	10.1	54.0
23	Mowata sil	168	240	800	175	5.6	1.66	13.0	47.0
24	Bernard cl	39	85	1200	391	5.9	1.66	15.5	53.7
--------------	- Mississippi Terraces & Loessial Hills Soils -	--------------							
25	Patoutville sil	21	36	316	98	4.9	1.12	8.0	30.2
26	Patoutville sil	78	60	250	86	4.6	1.12	9.2	24.5
27	Patoutville sil	44	45	1200	144	7.5	0.91	8.9	58.9
28	Jeanerette sil	123	95	1350	197	6.9	1.48	11.9	55.7
29	Jeanerette sil	24	40	1232	240	5.2	2.08	16.5	43.0

determined simultaneously by extracting 5 grams of soil with 1 N sodium acetate, adjusted to pH 4.5, at a soil to extracting solution ratio of 1:10. The soil and extracting solution were agitated for 15 minutes on a mechanical shaker. The soil and extracting solutions were filtered through Whatman No. 42 filter paper and the contents of zinc, iron, and manganese were determined on a Perkin-Elmer Model 303 atomic absorption spectrophotometer.

In all of the experiments conducted in the greenhouse, 2000 grams of soil on an oven dry basis, were placed in 3 liter plastic-lined containers. The soils in the containers were then treated as outlined in the explanation of individual experiments. The water used in all of the experiments was distilled and deionized.

In all of the experiments, the soil in the containers received a preplant application of 50 ppm of nitrogen as urea. The moisture content of the soil in each container was adjusted to approximately 80% of field capacity and maintained at this moisture content by the daily addition of water. Twelve rice seeds were planted in each container. One week after emergence, the plants were thinned to eight plants per container. Two weeks after emergence, the soil in the containers comprising the flooded treatments was submerged to a depth of approximately 2 cm with water. One week later, the depth of the water was increased to approximately 6 cm and this depth was maintained for the duration of the experiment. The moisture content of the soil in the containers comprising nonflooded treatments was maintained at approximately 80% of field capacity by the daily addition of water. Four weeks after emergence, the rice plants in all of the experiments were top-dressed with urea at a rate equivalent to 25 ppm of nitrogen. The plants were sprayed with an aqueous solution containing formanidine to control spider mites when the first infestation was observed.

The rice plants grown in all of the experiments were harvested eight weeks after seeding. The plants were cut at the ground level, placed in cloth bags, and dried in a forced draft oven for 36 hours at 60C. The plant material was weighed and the oven dried weights were recorded. The plant material was then ground in a stainless steel Wiley mill to pass a 20 mesh screen. The ground plant material was thoroughly mixed and stored in 125 ml screw top glass containers for future chemical analysis.

Immediately before the chemical determinations were made, the plant material was dried in a convection oven at 60C to remove any excess moisture that may have accumulated during sample preparation and storage. The plant material was digested in a mixture of concentrated nitric and perchloric acids on a hot plate according to the methods and procedures reported by Toth et al. (1948). To insure the precipitation of silica, 5 ml of 5 N HCl were added to the digested plant material. The digested material was filtered through Whatman No. 40 filter paper to remove silica and the filtrate was diluted to a volume of 100 ml with distilled water. A Perkin-Elmer Model 303 atomic absorption spectrophotometer was used to determine the concentration of potassium, calcium, magnesium, zinc, iron, and manganese in the plant material. Phosphorus was measured using the vanado-molybdate method as described by Jackson (1958). The intensity of the yellow color developed was measured on a Bausch and Lomb Model 20 Spectrophotometer.

An experiment was conducted to study the effects of flooding and applications of zinc and lime on the production of dry matter, the chemical composition, and the uptake of zinc, iron, and manganese by Saturn rice plants grown on a Patoutville silt loam soil (sample no. 26). Two water regimes, flooded and nonflooded; five rates of lime, the equivalent of 0, 1, 2, 3, and 4 tons per acre; and two rates of zinc, 5 ppm of zinc and no zinc, were included in a complete factorial experiment with 20 treatment combinations. Four replications of each of the 20 treatment combinations were arranged in a complete, randomized block design.

Reagent grade calcium carbonate was used as the source of lime. The calcium carbonate was thoroughly incorporated into the soil by mixing. After incorporation of the calcium carbonate, the moisture content of the soil was adjusted to approximately 80% of field capacity and maintained at this moisture content by daily addition of water for a period of three weeks. Three weeks after the addition of the calcium carbonate, reagent grade $ZnSO_4$, at a rate equivalent to 5 ppm of Zn was applied to the soil in 40 of the containers. The $ZnSO_4$ was thoroughly incorporated into the soil by mixing.

The nitrogen fertilization, the seeding rate, the harvesting, and the processing of the rice plants were accomplished in the manner previously described. The moisture content of the soil in the containers of the flooded and nonflooded treatments was initiated and maintained as previously described.

The second experiment was conducted to study the influence of flooding on the production of dry matter and on the concentration and uptake of zinc, iron, and manganese by Saturn rice plants grown on eight soils. Two water regimes, flooded and nonflooded, and eight soils were included in a complete factorial experiment with 16 treatment combinations. Three replications of each of the 16 treatment combinations were arranged in a complete, randomized block design. The soils used in the experiment were: Gallion silt loam, sample no. 2, Hebert silt loam, sample no. 4, Norwood silt loam, sample no. 8, two Acadia silt loams, samples no. 15 & 16, two Crowley silt loams, samples no. 17 & 18, and Patoutville silt loam, sample no. 26.

The nitrogen fertilization, seeding rate, and the harvesting and processing of the rice plants were accomplished in the manner previously described. The moisture content of the soil in the containers of the flooded and the nonflooded treatments was initiated and maintained as previously described.

The third experiment was conducted to study the effects of water treatments and applications of MnO_2 and $ZnSO_4$ on the production of dry matter and on the concentration and uptake of zinc, iron, and manganese by Saturn rice plants grown on Crowley silt loam, sample no. 18. The experiment consisted of four replications of six treatments arranged in a complete, randomized block design. The treatments were: (a) nonflooded, (b) nonflooded and $ZnSO_4$, (c) continuous flooding,

(d) continuous flooding and $ZnSO_4$, (e) continuous flooding and MnO_2, and (f) alternate flooding and draining.

Reagent grade $ZnSO_4$, at a rate equivalent to 5 ppm of Zn, was thoroughly incorporated into the soil in each container in treatments (b) and (d). Reagent grade MnO_2, at a rate equivalent to 0.5% of the amount of dry soil per container, was thoroughly incorporated into the soil of each of the containers in treatment (e).

The nitrogen fertilization, the seeding rate, and the harvesting and processing of the rice plants were accomplished in the manner previously described. The moisture content of the soil in the containers included in the flooded and the nonflooded treatments was initiated and maintained as previously described. The soil in the containers included in treatment (f) was flooded two weeks after emergence of the rice plants. Two weeks after the initial flooding, the soil in the containers was drained and the soil moisture content was maintained at approximately 80% of field capacity for one week. The soil was then reflooded for another two week interval. This cycle of alternate flooding and draining was continued for the duration of the experiment.

The fourth experiment was conducted to study the effects of applications of different types of organic matter and zinc on the production of dry matter and on the concentration and uptake of zinc, iron, and manganese by Saturn rice plants grown under flooded conditions on Crowley silt loam, sample no. 21. The experiment consisted of four replications of five treatments arranged in a complete, randomized block design. The treatments were: (a) check, (b) ground soybean leaves, (c) ground rice straw, (d) alpha cellulose powder and (e) $ZnSO_4$ powder.

The soybean leaves and rice straw were ground in a stainless steel Wiley mill to pass a 20 mesh screen. The alpha cellulose and the zinc sulphate were reagent grade powdered materials.

Four weeks prior to planting, 20 grams each of ground soybean leaves, rice straw, and alpha cellulose were incorporated into the soil of each of the containers included in the respective treatments. Nitrogen, at a rate of 50 ppm of N as urea was applied to the soil in each of the containers included in all of the treatments. The moisture content of the soil in each container was adjusted and maintained at approximately 80% of field capacity by the daily addition of water for four weeks prior to planting the rice seeds. Immediately before planting, reagent grade $ZnSO_4$, at a rate equivalent to 5 ppm of Zn, was incorporated into the soil in each of the containers included in treatment (e).

The application of nitrogen, used as a topdressing, the seeding rate, and the harvesting and processing of the plants were accomplished in the manner previously described. The soil in each container was flooded two weeks after emergence of the rice plants and maintained in the manner previously described.

The fifth experiment was conducted to determine if there were differential responses to the application of zinc, by rice varieties grown under flooded conditions on Crowley silt loam, sample no. 21. Three short grain, three medium grain, and three long grain varieties of rice were included in the experiment. The three short grain varieties were: Caloro, Calusa, and Taichung Native #1. The three medium grain varieties were: Vista, Saturn, and IR-8. The three long grain varieties were: Dawn, Bluebelle, and Starbonnet. All of the seed of the different varieties of rice were obtained from Mr. Nelson Jodon at the Rice Experiment Station at Crowley, Louisiana. The nine rice varieties with two rates of zinc, zinc and no zinc, were included in a complete factorial experiment with 18 treatment combinations. Four replications of each of the 18 treatment combinations were arranged in a complete, randomized block design.

Reagent grade $ZnSO_4$, at a rate equivalent to 5 ppm of Zn, was thoroughly incorporated into the soil in each of 36 containers. The nitrogen fertilization, the seeding rate, the flooding of the soil in the containers, and the harvesting and processing of the plants were accomplished in the manner previously described.

The sixth and final experiment was conducted to study the effects of applications of zinc on the production of dry matter and on the concentration and uptake of zinc, iron, and manganese by Saturn rice plants grown under flooded conditions on soils collected from different locations in Louisiana. The soils selected represented five major areas of the state and the textual classes ranged from fine sandy loams to clay loams. Two rates of zinc, zinc and no zinc, with 29 soils were included in a complete factorial experiment with 58 treatment combinations. Three replications of each of the 58 treatment combinations were arranged in a complete, randomized block design.

Reagent grade $ZnSO_4$, at a rate equivalent to 5 ppm of Zn, was incorporated into the soil in 87 of the containers. The nitrogen fertilization, the seeding rate, the flooding of the soil in the containers, and the harvesting and processing of the plants were accomplished in the manner previously described.

RESULTS AND DISCUSSION

The extractable manganese, iron, and zinc contents of the soils used in the greenhouse and laboratory investigations are presented in Table 3. The 1 N sodium acetate extractable manganese contents of the soils ranged from a low of 4 ppm in the Ruston fine sandy loam, sample no. 14, to a high of 170 ppm in the Mowata silt loam, sample no. 23. The 1 N sodium acetate extractable iron contents of the soils ranged from a low of 4 ppm in the Norwood silt loam, sample no. 9, and the Yahola very fine sandy loam, sample no. 10, to a high of 46 ppm in the Hebert silt loam, sample no. 3. The 0.1 N HCl extractable zinc contents of the soils ranged from a low of 1.1 ppm in the Crowley silt loam, sample no. 21, to a high of 10.1 ppm in the Mowata silt loam, sample no. 23.

The relatively high content of extractable zinc found in the Mowata silt loam was due to an application of zinc sulphate that was made to rice prior to the time of soil sample collection. The relatively high content of zinc found in the Mhoon silty clay loam, sample no. 1, may have been due to residual zinc resulting from the inclusion of zinc sulphate in the insecticidal spray for citrus.

Only two of the soils included in the investigation were considered to be critically low in extractable zinc for the production of rice. The two Crowley silt loam soils, samples no. 18 and 21, contained 1.2 and 1.1 ppm of zinc, respectively, and these contents of

Table 3. The extractable manganese, iron, and zinc contents of the soil samples used in greenhouse and laboratory investigations.

Sample Number	Soil Type	Concentration Mn 1/	Fe 1/	Zn 2/
		- - - - - - ppm- - - - - - -		
- - - - - - - - - - Mississippi River Alluvial Soils- - - - - - - - -				
1	Mhoon sicl	114	5	8.2
- - - - - Alluvial Soils of the Ouachita & Arkansas Rivers- - - - -				
2	Gallion sil	24	9	2.0
3	Hebert sil	21	46	1.7
4	Hebert sil	70	5	1.6
5	Hebert sil	137	8	3.9
- - - - - - - - - - -Alluvials Soils of the Red River- - - - - - - - -				
6	Pulaski vfsl	108	12	1.5
7	Norwood sil	30	5	2.7
8	Norwood sil	39	6	2.9
9	Norwood sil	12	4	2.0
10	Yahola vfsl	31	4	3.9
11	Yahola vfsl	16	9	1.5
- - - - - - - - - - -Coastal Plains & Flatwoods Soils- - - - - - - - -				
12	Bowie fsl	12	13	2.7
13	Shubuta fsl	55	6	2.0
14	Ruston fsl	4	5	1.4
- - - - - - - - - - - Soils of the Coastal Prairies - - - - - - - - - -				
15	Acadia sil	22	5	2.2
16	Acadia sil	101	11	4.8
17	Crowley sil	36	5	2.1
18	Crowley sil	69	5	1.2
19	Crowley sil	56	6	1.4
20	Crowley sil	81	19	3.9
21	Crowley sil	39	9	1.1
22	Morey sil	10	8	1.9
23	Mowata sil	170	39	10.1
24	Bernard cl	17	32	2.9

(Continued)

Table (Continued).

Sample Number	Soil Type	Concentration		
		Mn 1/	Fe 1/	Zn 2/
		- - - - - -ppm- - - - - - - -		
- - - - - - - - - Mississippi Terraces & Loessial Soils- - - - - - - -				
25	Patoutville sil	105	12	1.9
26	Patoutville sil	140	22	2.9
27	Patoutville sil	34	9	3.1
28	Jeanerette sil	93	7	3.9
29	Jeanerette sil	46	8	2.6

1/ Manganese and iron were extracted with 1 N sodium acetate, adjusted to pH 4.5.

2/ Zinc was extracted with 0.1 N HCl.

dilute acid extractable zinc have been found to be marginal for the optimum yield of rice. Zinc deficiency in rice grown on Prairie soils in Louisiana has been reported under field conditions when the zinc content of the soil, determined by extracting the soil with 0.1 N HCl, was 1.2 ppm or below (Sedberry et al., 1971). Soil test calibration data for zinc is not available for rice and other row crops grown on the alluvial soils of the Mississippi River, the Ouachita and Arkansas Rivers, and the Red River and soils comprising areas in the Coastal Plains and Flatwoods and soils of the Mississippi Terraces and Loessial Hills.

Statistically significant negative relationships were found between percent base saturation and extractable manganese, r = -0.421, and between percent base saturation and extractable iron, r = -0.423. The percent base saturation was not significantly related to the extractable zinc content of the soils. Soil reaction (pH) was negatively related to the extractable iron content, r = -0.522, of the soils. Soil reaction was not significantly related to either the extractable manganese content, or to the extractable zinc content of the soils. A statistically significant positive relationship was calculated between the extractable zinc and extractable manganese contents of the soils, r = 0.609. The extractable zinc content of the soils was also related to the cation exchange capacity, r = 0.562. A statistically significant positive relationship was found to exist between the extractable zinc content and the extractable phosphorus content, r = 0.495, and between the extractable zinc content and the extractable potassium content, r = 0.701, of the soils.

The effects of flooding and applications of zinc and lime on the production of dry matter and on the concentration and the uptake of zinc, iron, and manganese by Saturn rice plants grown on Patoutville silt loam, sample no. 26, are presented in Table 4 and in Figures 1, 2, 3, 4, 5, 6, and 7.

The data presented in Table 4 and Figure 1 indicated that the amount of dry matter produced under flooded soil conditions was significantly greater than that produced under nonflooded soil conditions. The observed increase in the amount of dry matter produced as a result of flooding is in agreement with results reported by Chaudhry and McLean (1963) and Senewiratne and Mikkelsen (1961).

The data indicate that, in general, the application of lime tended to reduce the amount of dry matter produced by the rice plants. Under both flooded and nonflooded soil conditions, with and without the application of zinc, the application of increasing rates of lime tended to result in a progressive decrease in the amount of dry matter produced by the rice plants. Under nonflooded soil conditions, the magnitude of the reduction in the amount of dry matter produced was not as great as that observed under flooded soil conditions. The observed influence of the application of lime on the production of dry matter produced by rice plants is consistent with the results reported by Khan (1969).

The effect of applications of zinc on the production of dry matter by the rice plants is presented in Table 4 and Figure 1. The data indicated that the influence of applications of zinc on the production

Table 4. The effects of flooding and applications of zinc and lime on the production of dry matter and the concentration and the uptake of zinc, iron, and manganese by Saturn rice plants grown on Patoutville silt loam.

Treatments		Dry	Concentration			Uptake		
Flooding	Zinc 1/	Matter	Zn	Fe	Mn	Zn	Fe	Mn
		g/pot	- - - - -ppm- - - - -			- - - - mg/pot- - - - -		
- - - No lime, pH 4.6- - -								
Flooded	Zn	12.4	148	147	4311	1.83	1.82	53.46
	No Zn	10.5	95	141	4969	1.00	1.49	52.17
Nonflooded	Zn	7.6	210	116	3020	1.67	0.88	22.96
	No Zn	6.8	131	121	2782	0.89	0.85	18.92
- - - -1 ton of lime, pH 5.5 - - -								
Flooded	Zn	8.2	115	167	2457	0.94	1.37	20.15
	No Zn	7.0	72	167	2980	0.51	1.17	20.86
Nonflooded	Zn	5.3	133	87	1164	0.71	0.46	6.17
	No Zn	5.1	83	124	1545	0.42	0.63	7.88
- - - -2 tons of lime, pH 6.0- - -								
Flooded	Zn	7.0	89	169	2046	0.62	1.19	14.32
	No Zn	5.9	69	165	2676	0.41	0.97	15.79
Nonflooded	Zn	5.2	74	83	804	0.39	0.43	4.18
	No Zn	4.4	64	113	989	0.28	0.50	4.35

(Continued)

Table (Continued)

Flooding	Zinc 1/	Dry Matter	Concentration Zn	Fe	Mn	Uptake Zn	Fe	Mn
		g/pot	- - - - -ppm- - - - -			- - - - mg/pot- - - -		
-3 tons of lime, pH 6.5-								
Flooded	Zn	5.1	107	155	6900	0.55	0.79	35.19
	No Zn	6.2	61	167	6235	0.38	1.04	38.66
Nonflooded	Zn	3.7	52	95	5673	0.27	0.35	20.99
	No Zn	4.1	48	111	6878	0.20	0.46	28.20
-4 tons of lime, pH 6.9-								
Flooded	Zn	4.9	88	152	5302	0.43	0.75	25.98
	No Zn	5.2	62	171	4692	0.32	0.89	24.40
Nonflooded	Zn	3.8	62	90	4245	0.24	0.34	15.13
	No Zn	3.4	44	97	5559	0.15	0.33	18.90
LSD, 5%		0.8	8	18	318	0.11	0.16	2.73

1/ Zinc was added at a rate equivalent to 5 ppm of Zn as $ZnSO_4$.

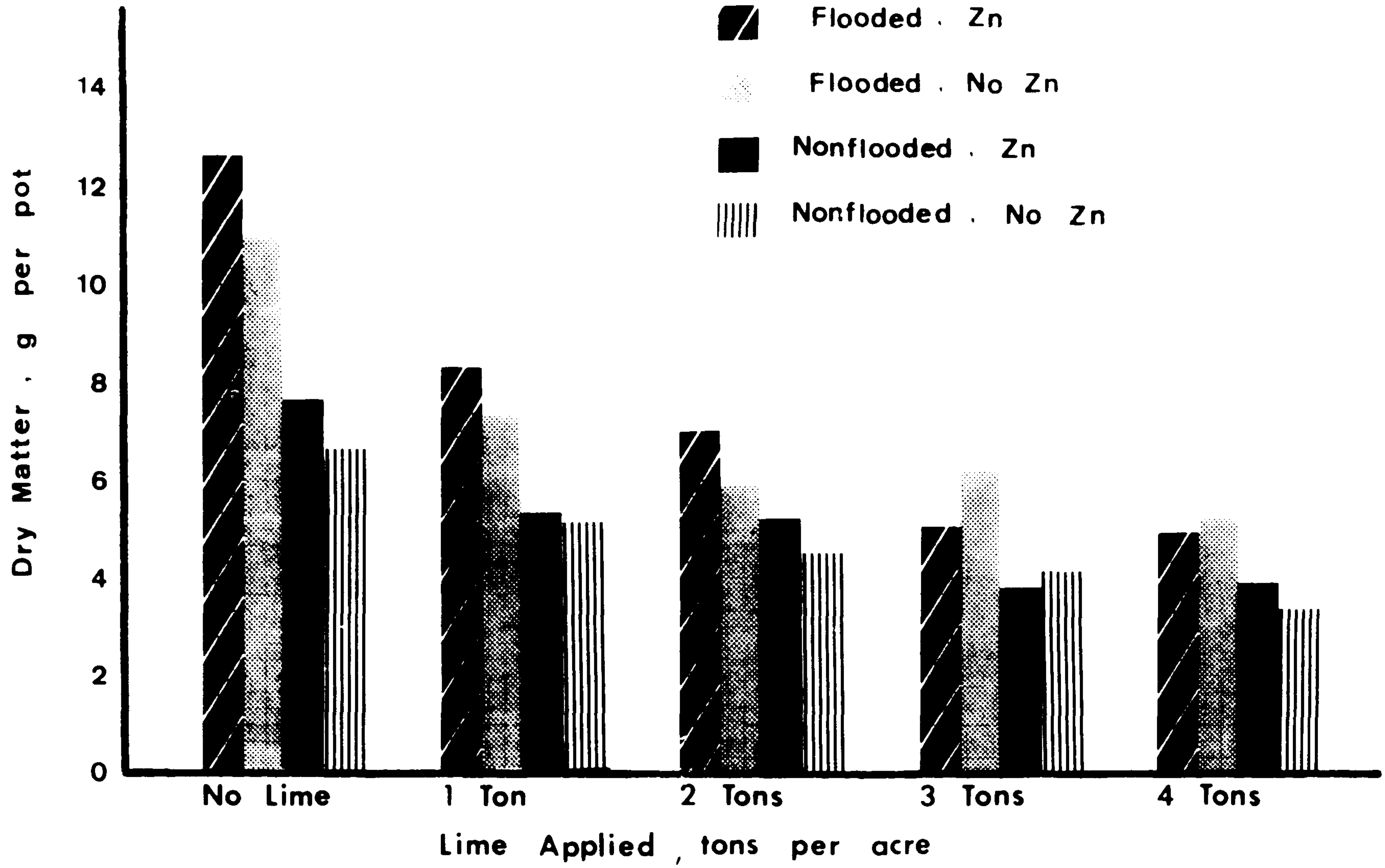

Figure 1. The effects of flooding and applications of zinc and lime on the production of dry matter by Saturn rice plants grown on Patoutville silt loam.

of dry matter depended on the flooding treatment and the amount of lime added. At the 0, 1, and 2 ton rates of lime, under flooded soil conditions, the application of zinc resulted in a statistically significant increase in the amount of dry matter produced by the rice plants. At the 3 ton lime rate, under flooded soil conditions, the application of zinc resulted in a significant decrease in the amount of dry matter produced when compared to that produced under similar conditions without the application of zinc. The application of zinc to the soil that received 4 tons of lime per acre caused a reduction in the amount of dry matter produced by the rice plants. However, the reduction was not statistically significant. Under nonflooded soil conditions, the application of zinc resulted in a significant increase in the amount of dry matter produced by the plants grown on the unlimed soil and the soil that received 2 tons of lime per acre. The influence of applications of zinc at the 1, 3, and 4 ton rates of lime varied from a slight increase to a slight decrease in the amount of dry matter produced by the rice plants grown under nonflooded soil conditions. However, none of the differences obtained at these lime rates were statistically significant.

On the unlimed soil, under both flooded and nonflooded soil conditions, the amount of dry matter produced by the rice plants was significantly increased by the application of zinc. Apparently, the Patoutville soil did not possess the necessary zinc supplying capacity to provide a sufficient amount of zinc for optimum growth of the rice plants. The application of zinc at the 1, 2, 3, and 4 ton rates of lime did not increase the growth of the rice plants to the level attained where no lime was applied. This suggested that the detrimental effect of applications of lime on the production of dry matter cannot be singularly attributed to the possible influence of lime on the uptake of zinc by the rice plants. If such had been the case, the application of zinc should have negated the influence of lime on the production of dry matter.

The data presented in Table 4 and in Figure 2 indicated that the influence of flooding on the concentration of zinc in the rice plants depended on the rate of lime applied. On the unlimed soil and the soil that received 1 ton of lime, with and without the application of zinc, flooding tended to decrease the concentration of zinc in the rice plants. At the 2, 3, and 4 ton lime rates, the concentration of zinc was higher in the plants grown on the flooded soil than it was in plants grown on the nonflooded soil. However, as indicated by the data presented in Figure 3, the total uptake of zinc by the rice plants grown under flooded soil conditions was greater than that of the plants grown under nonflooded soil conditions. The greater uptake of zinc can be attributed to the increased dry matter production by the plants grown under flooded conditions.

The data presented in Table 4 and Figures 2 and 3 indicated that, in general, the application of lime reduced both the concentration and the uptake of zinc by the rice plants. The magnitude of reduction in the zinc concentrations of the plants grown under nonflooded soil conditions appeared to be greater than that in the plants grown under

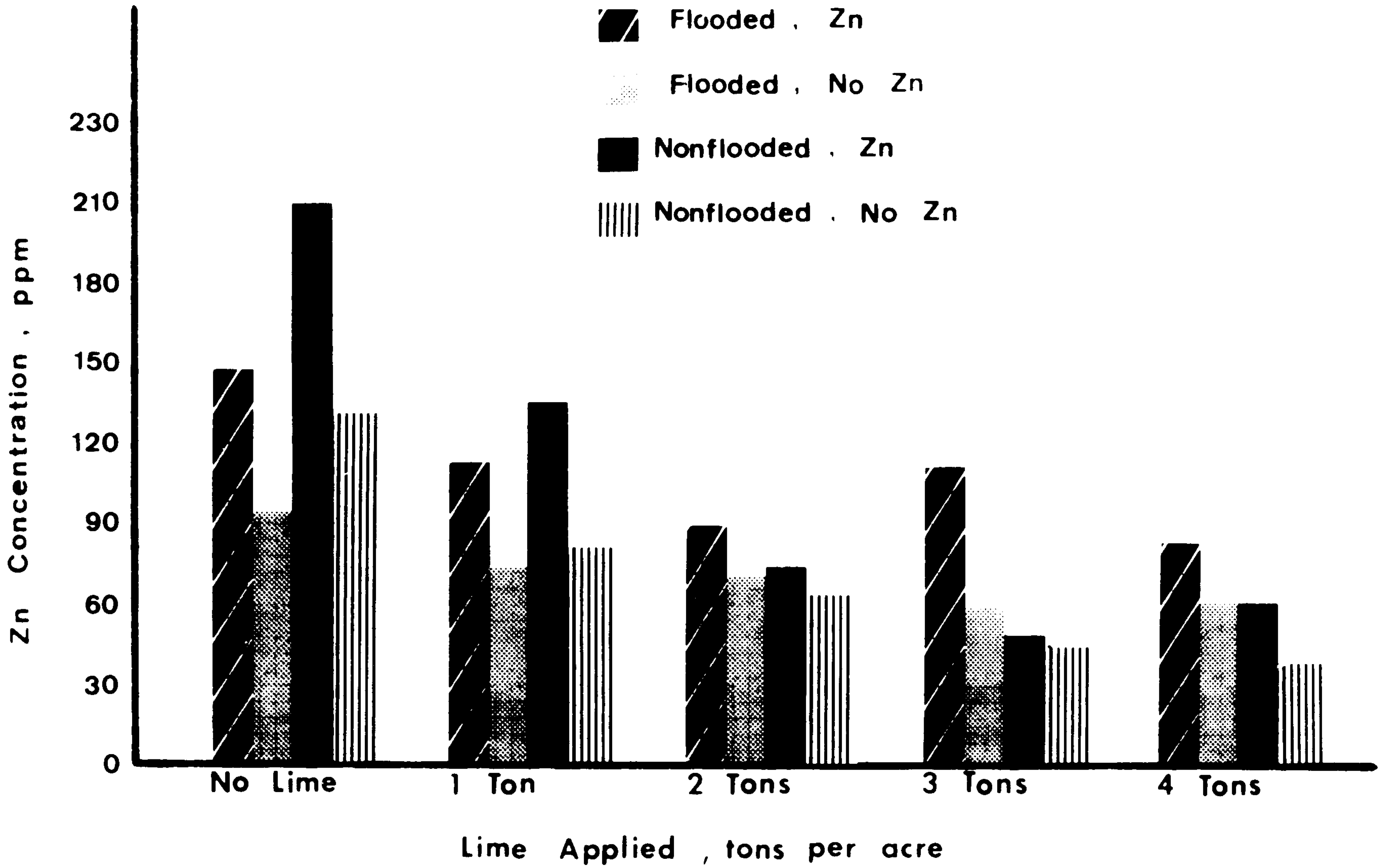

Figure 2. The effects of flooding and applications of zinc and lime on the concentration of zinc in Saturn rice plants grown on Patoutville silt loam.

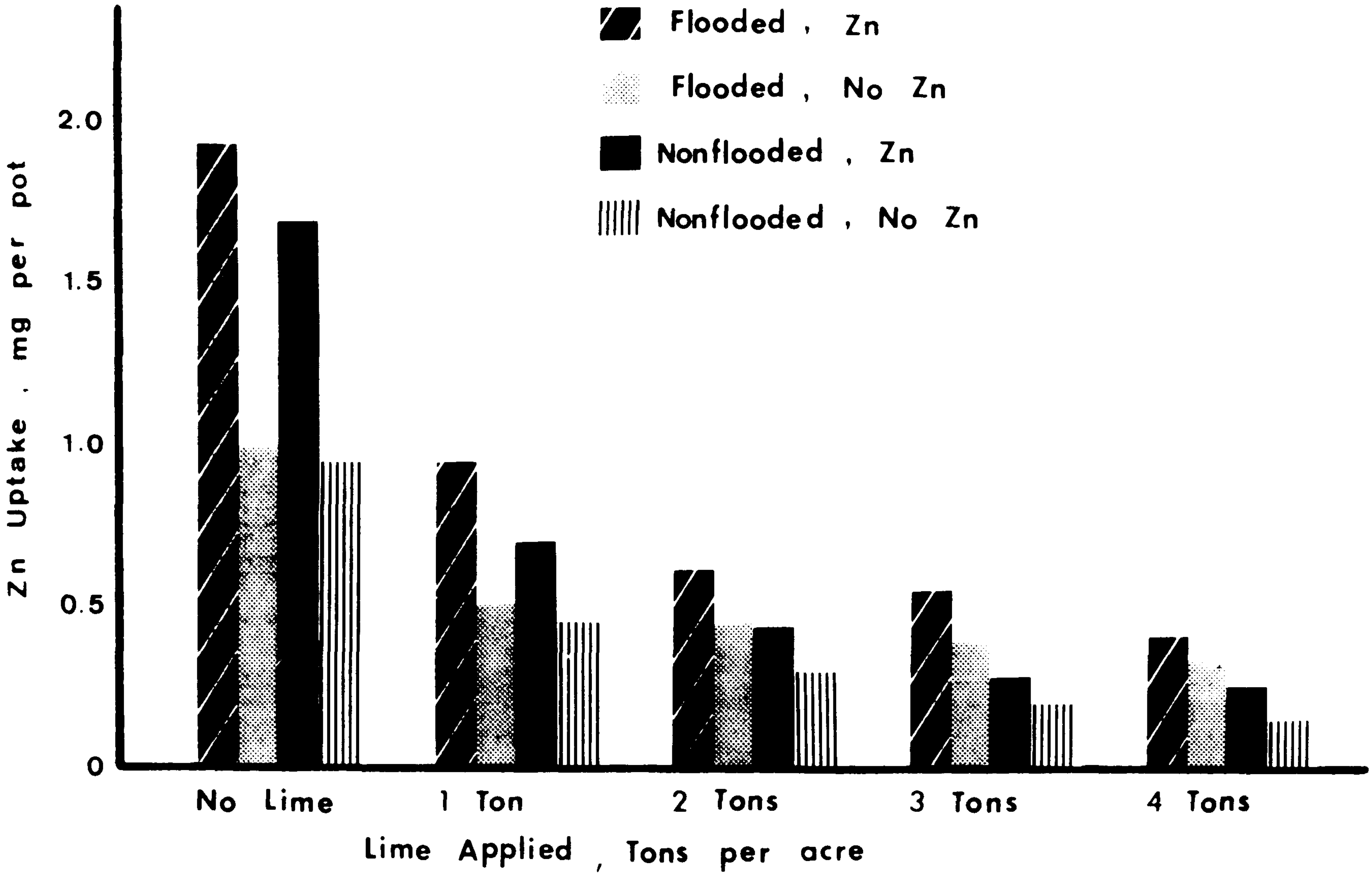

Figure 3. The effects of flooding and applications of zinc and lime on the uptake of zinc by Saturn rice plants grown on Patoutville silt loam.

flooded soil conditions. The uptake of zinc was consistently and progressively reduced by the application of increasing rates of lime. However, not all the differences were statistically significant.

With one exception, the application of zinc resulted in a significant increase in the concentration of zinc in the rice plants. The zinc concentration in the plants grown at the 3 ton rate of lime, on the nonflooded soil, was not significantly increased by the application of zinc. No explanation can be offered as to why the application of zinc did not result in a significant increase in the concentration of zinc in the plants grown under nonflooded conditions at the 3 ton rate of lime. With two exceptions, the application of zinc resulted in a significant increase in the uptake of zinc by the rice plants. The uptake of zinc by the plants grown at the 3 ton and the 4 ton rates of lime, on the nonflooded soil, was not significantly increased by the application of zinc.

As shown by the data presented in Table 4 and Figures 4 and 5, the concentration and the uptake of iron by the rice plants grown on the flooded soil were significantly greater than that of the plants grown on the nonflooded soil. The observed influence of flooding on the concentration and the uptake of iron by rice plants is consistent with results reported by Senewiratne and Mikkelsen (1961), and Chaudhry and McLean (1963).

The data presented in Table 4 and Figure 4 indicated that the influence of lime on the concentration of iron in the rice plants depended on the flooding and the zinc treatments. On the flooded soil,

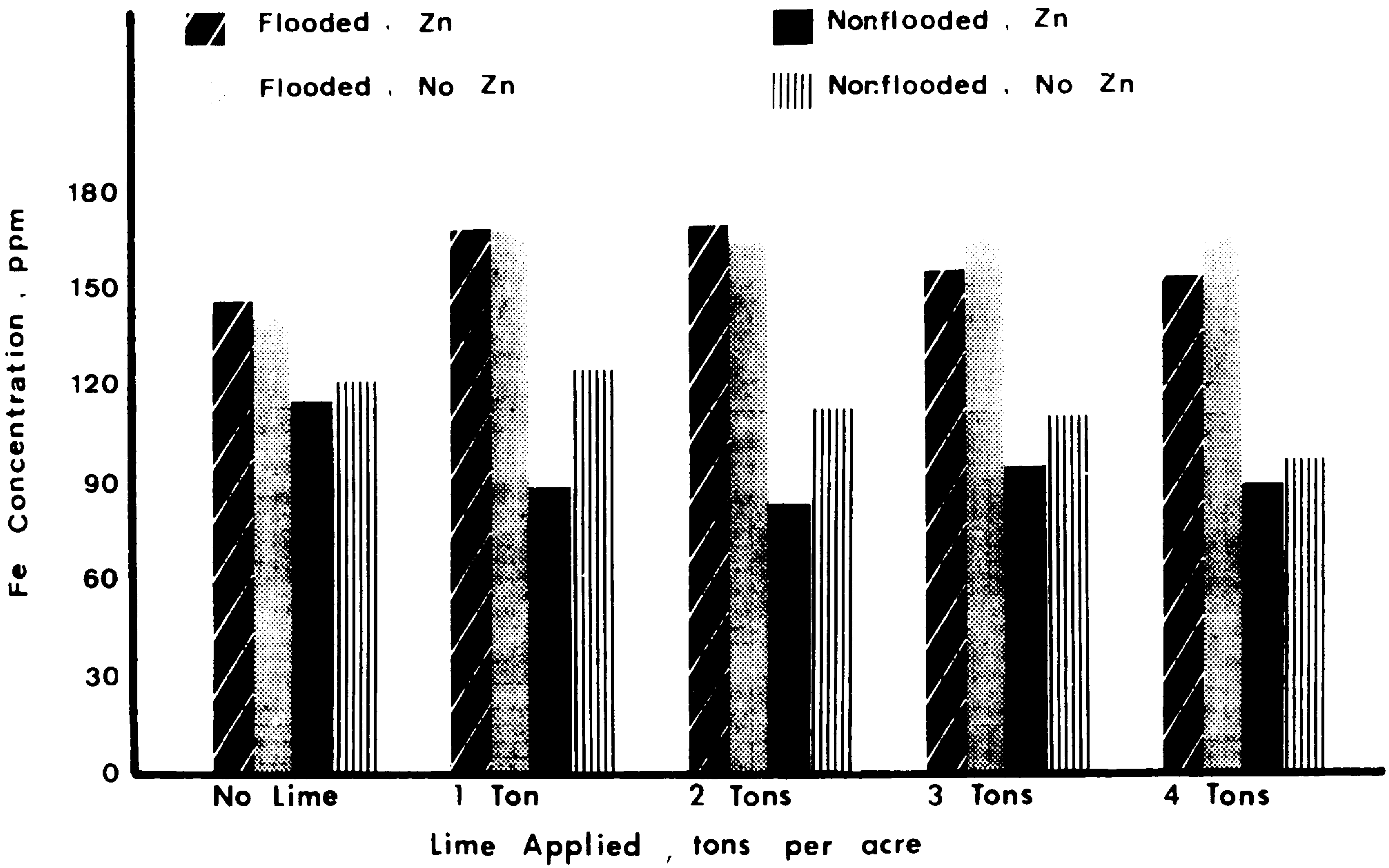

Figure [illegible]. The effects of flooding and applications of zinc and lime on the concentration of iron in Saturn rice plants grown on Patoutville silt loam.

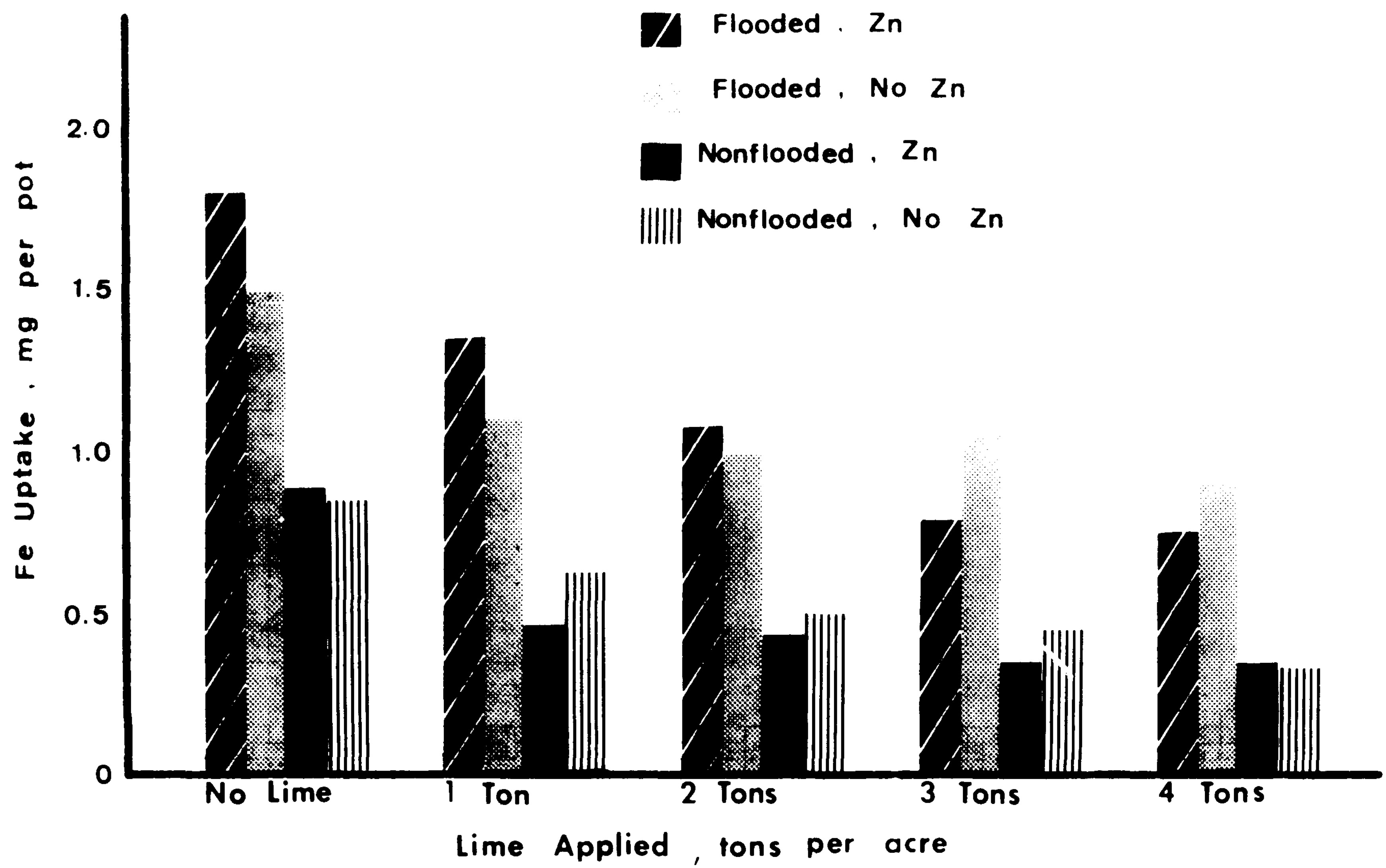

Figure 5. The effects of flooding and applications of zinc and lime on the uptake of iron by Saturn rice plants grown on Patoutville silt loam.

with and without the application of zinc, the application of 1 ton of lime resulted in a significant increase in the concentration of iron in the plants. However, the application of 2, 3, and 4 ton rates of lime did not result in a further significant increase in the concentration of iron in the plants. On the nonflooded soil where zinc was applied, the concentration of iron in the plants was significantly reduced by the application of 1 ton of lime. However, the application of the 2, 3, and 4 ton rates of lime did not cause a further significant reduction in the concentration of iron in the plants grown on the nonflooded soil that had received applications of zinc. On the nonflooded soil when zinc was not applied, the concentration of iron in the plants tended to be progressively reduced by the application of increasing rates of lime. However, all of the differences were not statistically significant. The data presented in Figure 5 indicated that the application of increasing rates of lime tended to result in a progressive decrease in the uptake of iron by the rice plants grown on the flooded and nonflooded soil with and without the application of zinc.

The data presented in Table 4 and Figures 4 and 5 indicated that the influence of applications of zinc on the concentration and uptake of iron in the rice plants appeared to depend on the lime and the flooding treatments. Where the application of zinc exerted a significant influence, the iron concentration was significantly reduced. The influence of applications of zinc varied from a statistically significant increase to a significant decrease in the uptake of iron. The data indicated that the influence of applications of zinc on the uptake of iron by the rice plants grown under flooded conditions, appeared to follow a trend. On the unlimed soil and the soil that received an application of 1 and 2 tons of lime, the application of zinc resulted in a significant increase in the uptake of iron by the plants grown under flooded conditions. At the 3 and 4 ton rates of lime, the application of zinc resulted in a decrease in the uptake of iron by the rice plants grown on flooded soil. The application of zinc to the nonflooded soil that received 1 ton of lime resulted in a significant decrease in the uptake of iron by the rice plants. Under nonflooded conditions, the zinc treatment had no significant effect on the uptake of iron by the plants grown on the unlimed soil and on the soil that received 2, 3, and 4 tons of lime.

The data presented in Table 4 and Figures 6 and 7 indicated that flooding the soil tended to increase the concentration and the uptake of manganese by the rice plants. With two exceptions, the concentration of manganese in the rice plants grown on the flooded soil was significantly greater than that in the plants grown on the nonflooded soil. At the 3 and 4 ton rates of lime where no zinc had been applied, the concentrations of manganese in the plants grown on the nonflooded soil were significantly greater than that of plants grown on flooded soil. However, the uptake of manganese by the rice plants was significantly increased by flooding at all rates of lime and both levels of zinc.

The data in Table 4 and Figures 6 and 7 indicated that the applications of 1 and 2 tons of lime per acre decreased the concentration and uptake of manganese by the rice plants on the flooded and nonflooded

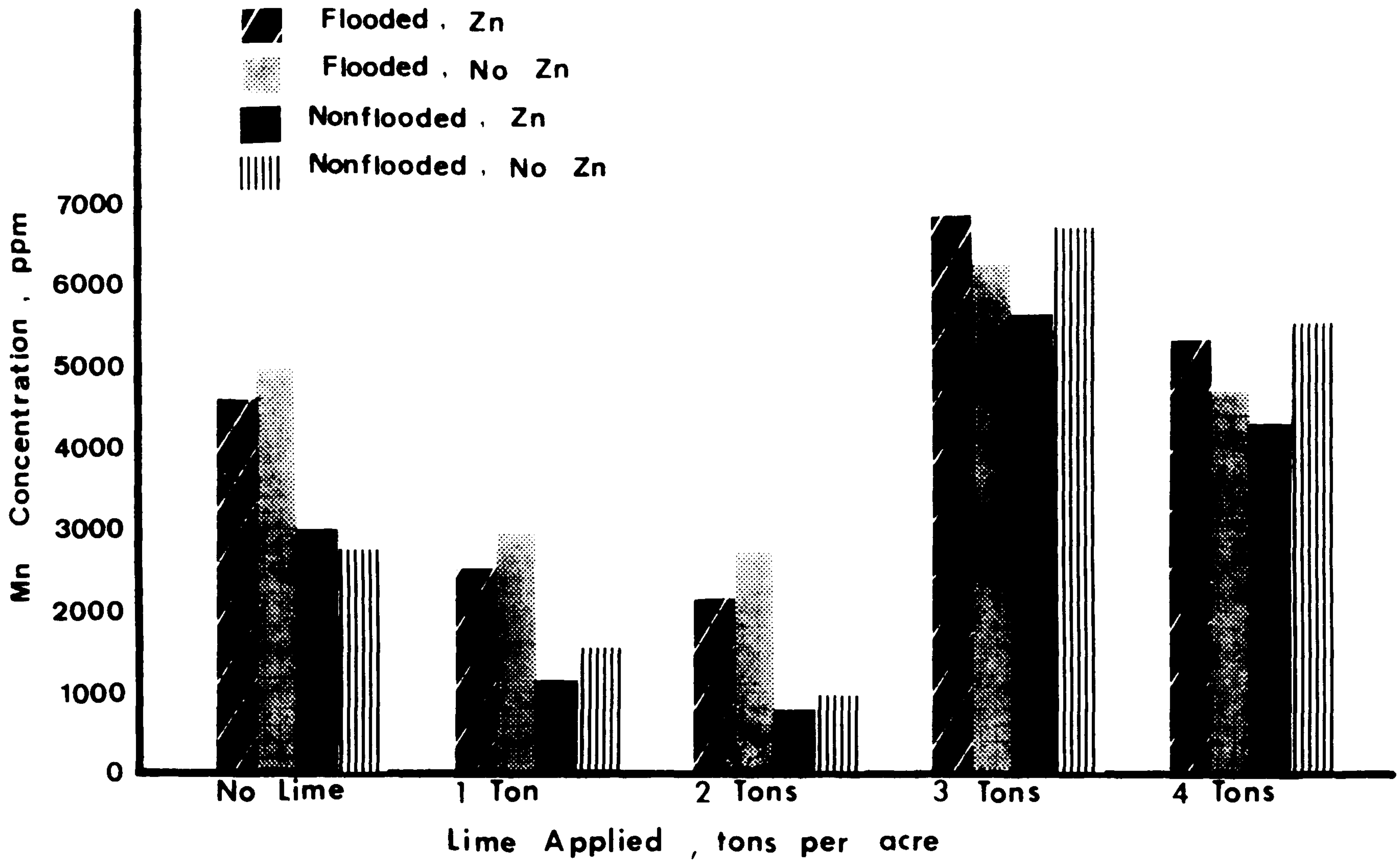

Figure 6. The effects of flooding and applications of zinc and lime on the concentration of manganese in Saturn rice plants grown on Patoutville silt loam.

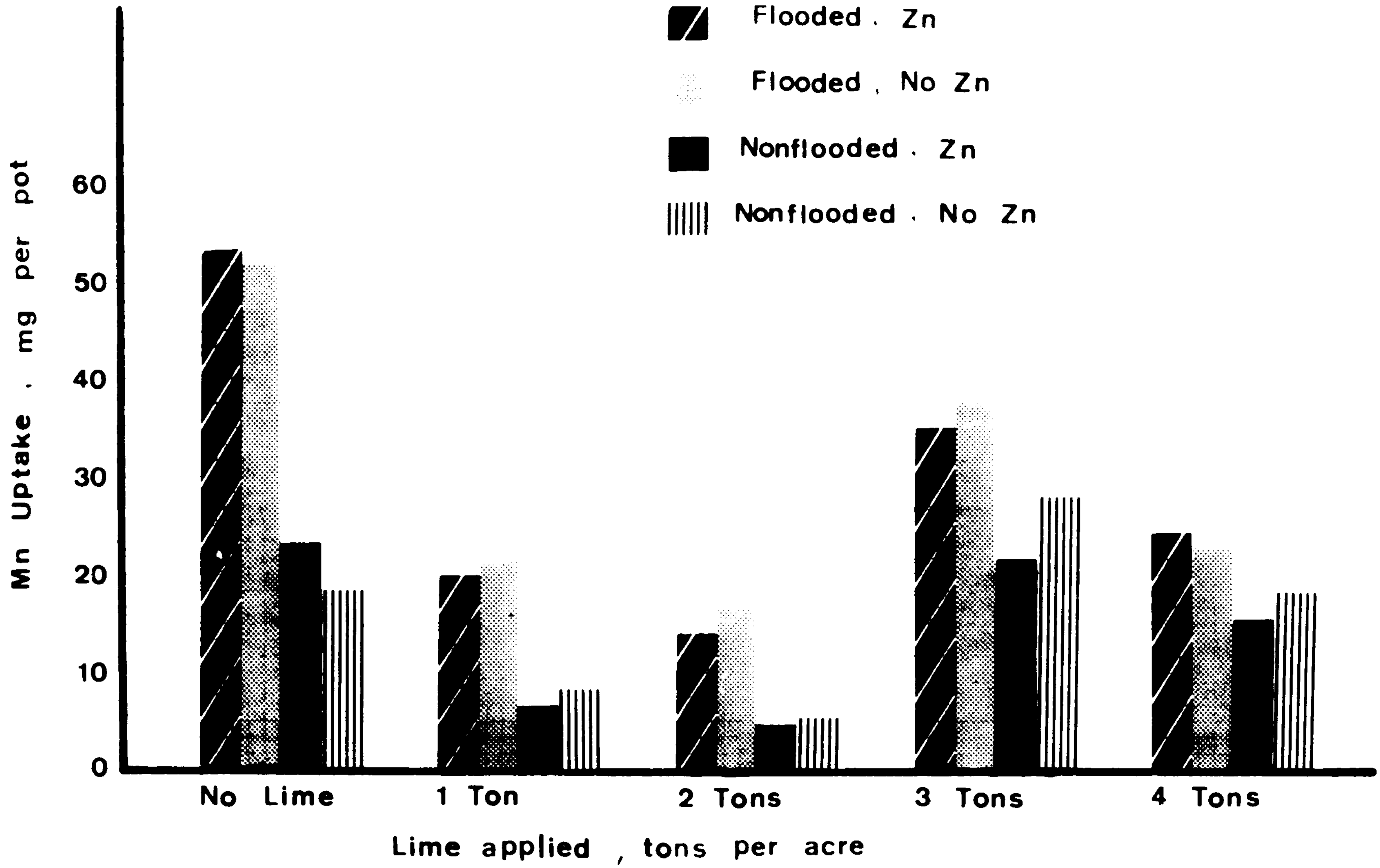

Figure 7. The effects of flooding and applications of zinc and lime on the uptake of manganese by Saturn rice plants grown on Patoutville silt loam.

soil irrespective to the application of zinc. However, when the soil reaction was adjusted to pH 6.5 and pH 6.9, following applications of 3 and 4 tons of lime per acre, the concentration and uptake of manganese by the rice plants were significantly increased. These results indicate that adjusting the soil reaction of the Patoutville silt loam from pH 6.0 to pH 6.5 and pH 6.9 increased the "availability" of indigenous soil manganese to the rice plants. These data are in agreement with those obtained by Jones (1956). He reported finding a greater concentration and uptake of manganese by oat plants grown on soil that had received applications of lime. Leeper (1970), in his discussion of the effect of pH on manganese availability reported that raising the pH of the soil by the application of lime is sometimes recommended as a practical step in increasing the availability of manganese in soils.

The effects of applications of zinc on the concentrations of manganese in the rice plants is shown in Table 4 and Figure 6. The data indicated that the effects of applications of zinc on the concentrations of manganese in the plants depended on both the flooding and the lime treatments. At rates of lime of 1 and 2 tons per acre, the application of zinc tended to reduce the concentration of manganese in the plants grown on the flooded and the nonflooded soil. At the 3 and 4 ton rates of lime, under flooded soil conditions, the application of zinc resulted in a significant increase in the manganese concentrations of the plants. However, at the 3 and 4 ton rates of lime, the application of zinc resulted in a significant decrease in the manganese concentration of the rice plants grown on the nonflooded soil. These data indicated that at the 3 and 4 ton rates of lime, the flooding treatments played a significant role in the influence of applications of zinc on the concentration of manganese in the rice plants.

The influence of applications of zinc on the uptake of manganese by the rice plants is shown in Table 4 and Figure 7. The data showed that on the unlimed soil, the application of zinc tended to increase the uptake of manganese by the rice plants grown on the flooded and nonflooded soil. The application of zinc tended to decrease the uptake of manganese by the rice plants grown on the flooded and nonflooded soil that received applications of 1, 2, 3, and 4 tons of lime per acre. However, all of the differences were not statistically significant.

The effects of flooding and the applications of zinc and lime on the production of dry matter and on the concentrations of phosphorus, potassium, calcium, and magnesium in Saturn rice plants grown on Patoutville silt loam are presented in Table 5. The data indicated that flooding the soil tended to increase the concentration of phosphorus in the rice plants. Except for the plants grown on the soil that received 2 tons of lime per acre and when no zinc was applied, flooding resulted in increases in the concentrations of phosphorus in the plant tissue. However, the increases were not all statistically significant.

The data indicated that the influence of lime on the phosphorus concentrations in the rice plants was dependent on both the flooding and the zinc treatments. The application of 1 ton of lime per acre

Table 5. The effects of flooding and applications of zinc and lime on the production of dry matter and on the concentration of phosphorus, potassium, calcium, and magnesium in Saturn rice plants grown on Patoutville silt loam.

Treatments		Dry	Concentration			
Flooding	Zinc 1/	Matter	P	K	Ca	Mg
		g/pot	ppm			
No lime, pH 4.6						
Flooded	Zn	12.4	1770	6000	3900	3909
	No Zn	10.5	2062	6200	4265	4219
Nonflooded	Zn	7.6	1604	11500	3100	4013
	No Zn	6.8	1604	10600	3763	4186
1 ton of lime, pH 5.5						
Flooded	Zn	8.2	1458	5800	4254	3693
	No Zn	7.0	1520	7450	4404	3323
Nonflooded	Zn	5.3	1104	10800	3975	4238
	No Zn	5.1	979	9850	4078	3536
2 tons of lime, pH 6.0						
Flooded	Zn	7.0	1520	7000	4124	3225
	No Zn	5.9	1333	9000	4523	2888
Nonflooded	Zn	5.2	1166	11050	3953	3715
	No Zn	4.4	1479	13850	4426	3166
3 tons of lime, pH 6.5						
Flooded	Zn	5.1	2020	18150	4410	3251
	No Zn	6.2	2187	15350	4844	3330
Nonflooded	Zn	3.7	1624	18600	4211	2959
	No Zn	4.1	1593	18600	4739	2541
4 tons of lime, pH 6.9						
Flooded	Zn	4.9	2332	18600	4676	3215
	No Zn	5.2	2270	17150	5009	3308
Nonflooded	Zn	3.8	1437	17450	4793	2849
	No Zn	3.4	1593	19250	5081	2996
LSD, 5%		0.8	268	923	189	224

1/ Zn was added as $ZnSO_4$ at a rate equivalent to 5 ppm Zn.

significantly reduced the concentrations of phosphorus in the plants grown under both flooded and nonflooded conditions irrespective of the zinc treatment. The influence of the application of additional rates of lime varied from a significant increase to a significant decrease in the concentration of phosphorus in the rice plants.

The influence of applications of zinc on the concentrations of phosphorus in the rice plants depended on the flooding and the lime treatments. The influence of applications of zinc varied from a non-significant increase to a significant decrease in the phosphorus concentrations in the rice plants.

The data indicated that flooding the soil tended to reduce the concentration of potassium in the rice plants. The one exception was that the concentration of potassium in the plants grown on the soil that had received 4 tons of lime per acre with zinc applied, was significantly greater when the plants were grown under flooded conditions. The differences between the potassium concentrations in the plants, as influenced by flooding the soil, were of much greater magnitude at the lower rates of lime.

The influence of applications of increasing rates of lime on the potassium concentrations in the rice plants appeared to follow a trend. The application of increasing rates of lime tended to result in increases in the potassium concentrations of the rice plants.

The influence of applications of zinc on the concentrations of potassium in the rice plants depended on the lime and the flooding treatments. The influence of zinc varied from a statistically significant increase to a statistically significant decrease in the potassium concentrations in the plants.

The data indicated that with one exception, the calcium concentrations in the rice plants grown on flooded soil were greater than the calcium concentrations in the plants grown on nonflooded soil. At the 4 ton rate of lime where zinc was applied, the concentration of calcium in the plants grown on the nonflooded soil was greater than the concentration of calcium in the plants grown on the flooded soil. The differences in the concentrations of calcium in the plants grown on flooded and nonflooded soil tended to become progressively smaller with increasing rates of lime.

The data indicated that with two exceptions, the application of increasing rates of lime tended to result in a progressive increase in the concentration of calcium in the plants. Under flooded and nonflooded conditions, when zinc was applied, the concentrations of calcium in the plants grown on the soil that received 1 ton of lime per acre were slightly greater than that of the plants grown on the soil that received 2 tons of lime.

Without exception, the concentrations of calcium in the plants grown on soil where no zinc was applied were greater than the concentrations of calcium in the plants grown on soil that had received an application of zinc. This suggested that applied zinc may have exerted an antagonistic and depressive effect upon the concentration of calcium in the rice plants.

The data indicated that the influence of flooding on the magnesium concentrations in the plants appeared to depend on the rate of lime applied. Flooding the soil tended to decrease the concentration of magnesium in the plants grown on the unlimed soil and on the soil that received 1 and 2 tons of lime. Flooding the soil resulted in a statistically significant increase in the concentrations of magnesium in the rice plants grown on soil that received 3 and 4 tons of lime per acre.

The influence of applications of increasing rates of lime on the concentrations of magnesium in the rice plants depended on the flooding and the lime treatments. The influence of applications of zinc on the concentrations of magnesium in the rice plants depended on the flooding and the lime treatment. The influence of applications of zinc varied from a statistically significant increase to a significant decrease in the concentration of magnesium in the plants.

The data in Table 5 indicated that flooding the Patoutville silt loam resulted in a significant increase in the amount of dry matter produced by the rice plants. There are several possible explanations for the observed increase in the amount of dry matter produced on the flooded soil. The influence of flooding on the soil and root temperatures may have been significant. The plants were grown in the greenhouse where midday atmospheric temperatures were often in excess of 45C. Although soil temperatures were not monitored, it seems reasonable to assume that the temperature of the flooded soil was lower than that of the nonflooded soil, and may have been more favorable for root development and plant growth.

The influence of flooding on the rate of tillering of the rice plants may also offer some explanation for the increase in the amount of dry matter produced under flooded soil conditions. The data presented in Table 6 indicated that flooding the soil increased the number of tillers produced by the plants, especially at the lower rates of lime. The increase in the number of tillers produced per container accounted for at least part of the increase in the amount of dry matter produced. The observed influence of flooding in the rate of tillering of the rice plants is consistent with the results reported by Cralley and Adair (1943).

The application of zinc at the 0, 1, and 2 ton rates of lime tended to increase the number of tillers produced by the rice plants. At the 3 and 4 ton rates of lime, the influence of applications of zinc on the rate of tillering was dependent on the lime and the flooding treatments.

The application of lime tended to decrease the number of tillers produced by the rice plants. The magnitude of the reduction in the number of tillers produced was greater when the plants were grown on the flooded soil.

The influence of flooding on the production of dry matter and on the concentration and the uptake of zinc, iron, and manganese by Saturn rice plants grown on eight soils is presented in Table 7.

The data indicated that flooding the soil resulted in significant increases in the amount of dry matter produced by the plants grown on the Gallion, Acadia, sample no. 16, Crowley, samples no. 17 and 18, and the Patoutville silt loams. The amount of dry matter

Table 6. The effects of flooding and application of zinc and lime on the production of dry matter and the rate of tillering of Saturn rice plants grown on Patoutville silt loam.

Treatments		Dry	Tillering
Flooding	Zinc 1/	Matter	Rate
		g/pot	number/pot 2/
-No lime, pH 4.6-			
Flooded	Zn	12.4	17.5
	No Zn	10.5	15.0
Nonflooded	Zn	7.6	4.8
	No Zn	6.8	4.0
1 ton of lime, pH 5.5			
Flooded	Zn	8.2	8.5
	No Zn	7.0	6.0
Nonflooded	Zn	5.3	2.0
	No Zn	5.1	1.5
2 tons of lime, pH 6.0-			
Flooded	Zn	7.0	5.0
	No Zn	5.9	3.5
Nonflooded	Zn	5.2	1.0
	No Zn	4.4	0.0
3 tons of lime, pH 6.5-			
Flooded	Zn	5.1	2.0
	No Zn	6.2	3.5
Nonflooded	Zn	3.7	0.0
	No Zn	4.1	0.0
4 tons of lime, pH 6.9-			
Flooded	Zn	4.9	2.0
	No Zn	5.2	2.0
Nonflooded	Zn	3.8	0.0
	No Zn	3.4	0.0

1/ Zinc added as $ZnSO_4$ at a rate equivalent to 5 ppm Zn.

2/ Average of four replications.

Table 7. The influence of flooding on the production of dry matter and on the concentration and the uptake of zinc, iron, and manganese by Saturn rice plants grown on eight soils.

Sample Number	Soil Type	Water Treatment	Dry Matter	Concentration Zn	Concentration Fe	Concentration Mn	Uptake Zn	Uptake Fe	Uptake Mn
			g/pot	- - - -ppm- - - -			- - - mg/pot- - - -		
2	Gallion sil	Flooded	9.4	31.5	239	1112	0.30	2.25	10.45
		Nonflooded	7.5	65.1	128	858	0.49	0.96	6.44
4	Hebert sil	Flooded	3.5	64.6	398	2217	0.23	1.39	7.76
		Nonflooded	5.9	40.2	116	156	0.24	0.69	0.92
8	Norwood sil	Flooded	9.9	28.4	225	711	0.28	2.23	7.04
		Nonflooded	9.8	37.1	85	61	0.36	0.83	0.60
15	Acadia sil	Flooded	1.5	64.0	446	200	0.10	0.67	0.30
		Nonflooded	2.6	47.3	144	100	0.12	0.38	0.26
16	Acadia sil	Flooded	19.8	83.5	274	2694	1.65	5.43	53.34
		Nonflooded	13.0	135.7	117	860	1.76	1.52	11.18
17	Crowley sil	Flooded	11.0	36.5	146	917	0.40	1.61	10.09
		Nonflooded	6.5	58.0	94	437	0.38	0.61	2.84
18	Crowley sil	Flooded	9.6	29.5	155	758	0.28	1.49	7.27
		Nonflooded	6.0	46.2	84	214	0.28	0.51	1.28
26	Patoutville sil	Flooded	12.8	127.3	281	4372	1.63	3.59	55.97
		Nonflooded	8.2	163.8	131	2609	1.34	1.08	21.39
LSD, 5%			1.9	21.2	47	172	0.29	0.50	5.02

produced by the plants grown on the Hebert silt loam was significantly reduced by flooding. The amount of dry matter produced by the rice plants grown on the Norwood silt loam and the Acadia silt loam, sample no. 16, was not significantly affected by flooding.

The data presented in Table 7 indicated that flooding the soil resulted in a statistically significant decrease in the concentration of zinc in the rice plants grown on the Gallion silt loam, the Acadia silt loam, sample no. 16, the Crowley silt loam, sample no. 17, and the Patoutville silt loam. Flooding the soil did not have a significant influence on the concentration of zinc in the plants grown on the Norwood silt loam, the Acadia silt loam, sample no. 15, and the Crowley silt loam, sample no. 18. Flooding the Hebert silt loam resulted in a significant increase in the concentration of zinc in the rice plants.

The uptake of zinc by the rice plants grown on the Patoutville silt loam was significantly increased by flooding. Flooding did not have a significant affect on the uptake of zinc by the rice plants grown on the other seven soils. Using uptake as a criterion for evaluating the "availability" of zinc, the data suggested that although flooding resulted in a significant reduction in the concentration of zinc in the rice plants grown on four of the soils, the "availability" of zinc to the plants was not significantly reduced by flooding.

Flooding resulted in a significant increase in the concentration of iron in the rice plants grown on all of the soils. Flooding the soil resulted in a significant increase in the uptake of iron by the rice plants grown on seven of the eight soils. The uptake of iron by the rice plants grown on the Acadia silt loam, sample no. 15, was not significantly affected by flooding.

Flooding the soil resulted in a significant increase in the concention of manganese in the rice plants grown on seven of the eight soils. The increase in the concentration of manganese in the rice plants grown on the Acadia silt loam, sample no. 15, was not statistically significant. Flooding the soil resulted in a statistically significant increase in the uptake of manganese by the rice plants grown on six of the eight soils. Flooding did not have a significant effect on the uptake of manganese by the plants grown on the Gallion silt loam and the Acadia silt loam, sample no. 15.

The data presented in Table 7 indicated that flooding resulted in a significant increase in the dry matter production by rice plants grown on five of the eight soils. There are several possible explanations for the observed influence of flooding on the dry matter production of the rice plants.

The influence of flooding on the production of dry matter and on the rate of tillering of Saturn rice plants grown on eight soils is presented in Table 8. The influence of flooding on the rate of tillering of the rice plants appeared to play a significant role in increasing the amount of dry matter produced by the rice plants grown on five of the eight soils. The data indicated that flooding the soil resulted in a significant increase in the number of tillers produced by the rice plants grown on the Gallion silt loam, the Norwood silt loam, the Acadia silt loam, sample no. 16, the two Crowley silt loams, samples no. 17 and 18, and the Patoutville silt loam. In every case where flooding resulted in a significant increase in dry matter production by the rice plants, the number of tillers produced by the plants was also siginificantly increased.

Table 8. The influence of flooding on the production of dry matter and on the rate of tillering of Saturn rice plants grown on eight soils.

Sample Number	Soil Type	Water Treatment	Dry Matter	Tillering Rate
			g/pot	number/pot 1/
2	Gallion sil	Flooded	9.4	9.7
		Nonflooded	7.5	2.0
4	Hebert sil	Flooded	3.5	0.0
		Nonflooded	5.9	0.0
8	Norwood sil	Flooded	9.9	4.7
		Nonflooded	9.8	1.9
15	Acadia sil	Flooded	1.5	0.0
		Nonflooded	2.6	0.0
16	Acadia sil	Flooded	19.8	14.3
		Nonflooded	13.0	3.3
17	Crowley sil	Flooded	11.0	12.0
		Nonflooded	6.5	3.3
18	Crowley sil	Flooded	9.6	10.7
		Nonflooded	6.0	2.7
26	Patoutville sil	Flooded	12.8	10.3
		Nonflooded	8.2	3.0
LSD, 5%			1.9	2.3

1/ Average of three replications.

The increased availability of manganese, as a result of flooding the soil, may also have been partially responsible for the increase in the amount of dry matter produced by the plants grown under flooded conditions. Significant positive relationships were calculated between the manganese concentration and the amount of dry matter produced, r = 0.480, and between the manganese uptake and the amount of dry matter produced, r = 0.738. The data presented in Table 7 indicated that in every case where flooding resulted in a significant increase in the amount of dry matter produced by the rice plants, the concentration of manganese by the plants was also significantly increased. A significant increase in the manganese uptake by the rice plants was noted on four of the five soils where flooding resulted in a significant increase in dry matter production.

The influence of flooding on the production of dry matter and on the concentration and the uptake of phosphorus by Saturn rice plants grown on eight soils is presented in Table 9. The influence of flooding the soil on the "availability" of phosphorus cannot be overlooked as being partially responsible for the observed increase in the amount of dry matter produced by the rice plants. This may have been of particular significance considering the fact that no additional phosphorus was applied to the soils.

The data indicated that except for the plants grown on the Gallion silt loam, flooding the soil resulted in a statistically significant increase in the concentration of phosphorus in the rice plants. No explanation can be offered as to why flooding resulted in a

Table 9. The influence of flooding on the production of dry matter and on the concentration and the uptake of phosphorus by Saturn rice plants grown on eight soils.

Number	Soil Type	Water Treatment	Dry Matter	Phosphorus Concentration	Phosphorus Uptake
			g/pot	ppm	mg/pot
2	Gallion sil	Flooded	9.4	4521	42.50
		Nonflooded	7.5	5454	40.91
4	Hebert sil	Flooded	3.5	4867	17.04
		Nonflooded	5.9	3171	18.39
8	Norwood sil	Flooded	9.9	2450	24.26
		Nonflooded	9.8	1209	11.85
15	Acadia sil	Flooded	1.5	2375	3.56
		Nonflooded	2.6	1313	3.41
16	Acadia sil	Flooded	19.8	2396	47.44
		Nonflooded	13.0	979	12.73
17	Crowley sil	Flooded	11.0	1441	15.85
		Nonflooded	6.5	938	6.10
18	Crowley sil	Flooded	9.6	1775	17.04
		Nonflooded	6.0	834	5.00
26	Patoutville	Flooded	12.8	4583	58.66
		Nonflooded	8.2	888	7.28
LSD, 5%			1.9	417	5.26

significant decrease in the concentration of phosphorus in the rice plants grown on the Gallion silt loam. Flooding resulted in an increase in the uptake of phosphorus by the rice plants grown on all but the Hebert silt loam. However, not all of the differences were statistically significant.

According to Chapman (1966), rice tissue that contains less than 1000 ppm of phosphorus is considered to be critically low in phosphorus. The data presented in Table 9 indicated that the phosphorus concentration was below 1000 ppm in the rice plants grown under nonflooded soil conditions on the Acadia silt loam, sample no. 16, Crowley silt loam, samples no. 17 and 18, and Patoutville silt loam. The flooding treatment significantly increased the amount of dry matter produced by the rice plants grown on all four of these soils. The data indicate that the increased "availability" of phosphorus to the plants grown under flooded soil conditions may have been a significant factor in the observed increase in the dry matter production by the rice plants.

The results suggested that no one factor alone was responsible for the increase in the amount of dry matter produced by the rice plants grown on the flooded soils. It appeared that the increased rate of tillering, the increased "availability" of manganese, and the increased "availability" of phosphorus may all have been significant factors.

The effects of water treatments and the application of manganese dioxide and zinc sulfate on the production of dry matter and on the concentration and the uptake of zinc, iron, and manganese by Saturn rice plants grown on Crowley silt loam, sample no. 18, are presented in Table 10.

The data indicated that the greatest amount of dry matter was produced by the rice plants grown under the conditions of continuous flooding and continuous flooding combined with the application of MnO_2. The application of zinc to the continuously flooded soil resulted in a significant decrease in the dry matter produced by the plants. The production of dry matter produced by the plants grown on the alternately drained soil was significantly lower than that produced by the plants grown under the conditions of any of the treatments which involved continuous flooding. The amount of dry matter produced by the plants grown on the alternately drained soil was significantly greater than that produced by the rice plants grown on the nonflooded soil with or without $ZnSO_4$. The application of zinc to the nonflooded soil had no significant influence on the production of dry matter by the rice plants.

The concentrations of zinc in the plants grown on the continuously flooded soil with and without MnO_2 were significantly lower than that in the plants grown on the nonflooded soil. The uptake of zinc by the plants grown on the soil that was continuously flooded with and without MnO_2 was significantly greater than was the uptake of zinc by the plants grown on the nonflooded soil. The application of zinc to the soil that was continuously flooded and to the nonflooded soil resulted in a significant increase in the concentration and the uptake

Table 10. The effects of water treatments and applications of manganese dioxide and zinc sulfate on the production of dry matter and on the concentration and the uptake of zinc, iron, and manganese by Saturn rice plants grown on Crowley silt loam.

Treatment	Dry Matter	Concentration			Uptake		
		Zn	Fe	Mn	Zn	Fe	Mn
	g/pot	- - - - - ppm- - - - -			- - - - mg/pot- - - -		
Unflooded	7.1	39.9	133	211	0.28	0.94	1.50
Continuous flooding	15.0	31.7	162	1127	0.48	2.43	16.90
Alternate drainage	10.7	34.9	228	673	0.37	2.44	7.20
Continuous flooding and MnO_2 1/	15.0	29.7	164	1505	0.45	2.47	22.57
Continuous flooding and $ZnSO_4$ 2/	13.7	72.3	223	895	0.99	3.06	12.17
Nonflooded and $ZnSO_4$ 2/	7.8	88.5	133	192	0.69	1.04	1.50
LSD, 5%	1.3	5.8	21	192	0.11	0.50	4.71

1/ MnO_2 was added at a rate equivalent to 0.5% of the amount of soil per pot.

2/ $ZnSO_4$ was added at a rate equivalent to 5 ppm of Zn.

of zinc by the rice plants when compared to that of the plants grown under similar conditions when zinc was not applied. The concentration of zinc in the plants grown on the soil that was alternately drained was not significantly different from the concentrations of zinc in the plants grown on the soil that was flooded continuously with or without MnO_2, or on the nonflooded soil.

The highest concentration of iron occurred in the plants grown on the soil that was alternately drained. The application of zinc to continuously flooded soil resulted in a significant increase in both the concentration and the uptake of iron by the rice plants. On the nonflooded soil, the application of zinc had no significant influence on either the concentration or the uptake of iron. The application of MnO_2 to the soil that was flooded continuously had no significant influence on either the concentration or the uptake of iron by the rice plants. Both the uptake and the concentration of iron in the plants grown on the soil that was flooded continuously were significantly greater than that of the rice plants grown on the nonflooded soil.

The application of MnO_2 to the continuously flooded soil resulted in a significant increase in both the concentration and the uptake of manganese by the rice plants. Under continuous flooding conditions, the application of zinc resulted in a significant decrease in the concentration and the uptake of manganese by the rice plants. On the nonflooded soil, the application of zinc had no significant influence on either the concentration or the uptake of manganese by the rice plants. The concentration and the uptake of manganese by the rice plants grown under continuous flooding conditions were significantly greater than that of the plants grown under nonflooded conditions. The concentration and the uptake of manganese by the rice plants grown under alternate drainage conditions were significantly greater than that of the plants grown on the nonflooded soil, but significantly lower than that of the plants grown on the continuously flooded soil.

The effects of water treatments and applications of manganese dioxide and zinc sulfate on the production of dry matter and on the concentration of manganese and iron and the manganese to iron ratio of Saturn rice plants grown on Crowley silt loam are presented in Table 11. The data suggested that the manganese to iron ratio was related to the dry matter produced. In general, as the manganese to iron ratio increased, the amount of dry matter produced by the rice plants also increased.

Under continuous flooding conditions, the application of zinc resulted in a reduction in the manganese to iron ratio of the rice plants. Since the manganese to iron ratio appeared to be related to the production of dry matter, the influence of applications of zinc on the manganese to iron ratio may offer some explanation for the observed decrease in the amount of dry matter produced by the rice plants grown under continuous flooding where zinc was applied. On the nonflooded soil, the application of zinc did not have a significant influence on the manganese to iron ratio of the rice plants. The

Table 11. The effects of water treatments and applications of manganese dioxide and zinc sulfate on the production of dry matter, the concentration of manganese and iron, and the manganese to iron ratio in Saturn rice plants grown on Crowley silt loam.

Treatment	Dry Matter	Concentration Mn	Fe	Mn:Fe Ratio
	g/pot	- - -ppm- - -		
Unflooded	7.1	211	133	1.59
Continuous flooding	15.0	1127	162	6.96
Alternate drainage	10.7	673	228	2.95
Continuous flooding and MnO_2 1/	15.0	1505	164	9.18
Continuous flooding and $ZnSO_4$ 2/	13.7	895	223	4.01
Nonflooded and $ZnSO_4$ 2/	7.8	192	133	1.44
LSD, 5%	1.3	192	21	

1/ MnO_2 was added at a rate equivalent to 0.5% of the amount of soil per pot.

2/ $ZnSO_4$ was added at a rate equivalent to 5 ppm of Zn.

application of MnO_2 resulted in a significant increase in the manganese to iron ratio of the rice plants. However, the increase in the manganese to iron ratio was not associated with an increase in the production of dry matter by the rice plants.

It has been noted that when compared to other agronomic crops, rice has a relatively high requirement and tolerance to manganese (Clark et al., 1957). The relationship between the production of dry matter and the concentration of manganese in Saturn rice plants grown under different water, zinc, and manganese treatments on Crowley silt loam is shown in Figure 8. A highly significant positive relationship between the manganese concentration and the production of dry matter by the rice plants, r = 0.895, was found in the experiment. The data indicated that as the concentration of manganese increased in the rice plants, the amount of dry matter produced tended to increase. The results suggested that the "availability" of manganese may have been a limiting factor in the growth of the rice plants under the conditions of the treatments where lower manganese concentrations were observed.

The concentration of manganese in the rice plants grown on the continuously flooded soil was considerably greater than that of the plants grown on the soil that was alternately drained or on the non-flooded soil. The amount of dry matter produced was also considerably greater. It seems reasonable to assume that the increased "availability" of manganese, as influenced by continuous flooding, was a significant factor in increasing the amount of dry matter produced. This

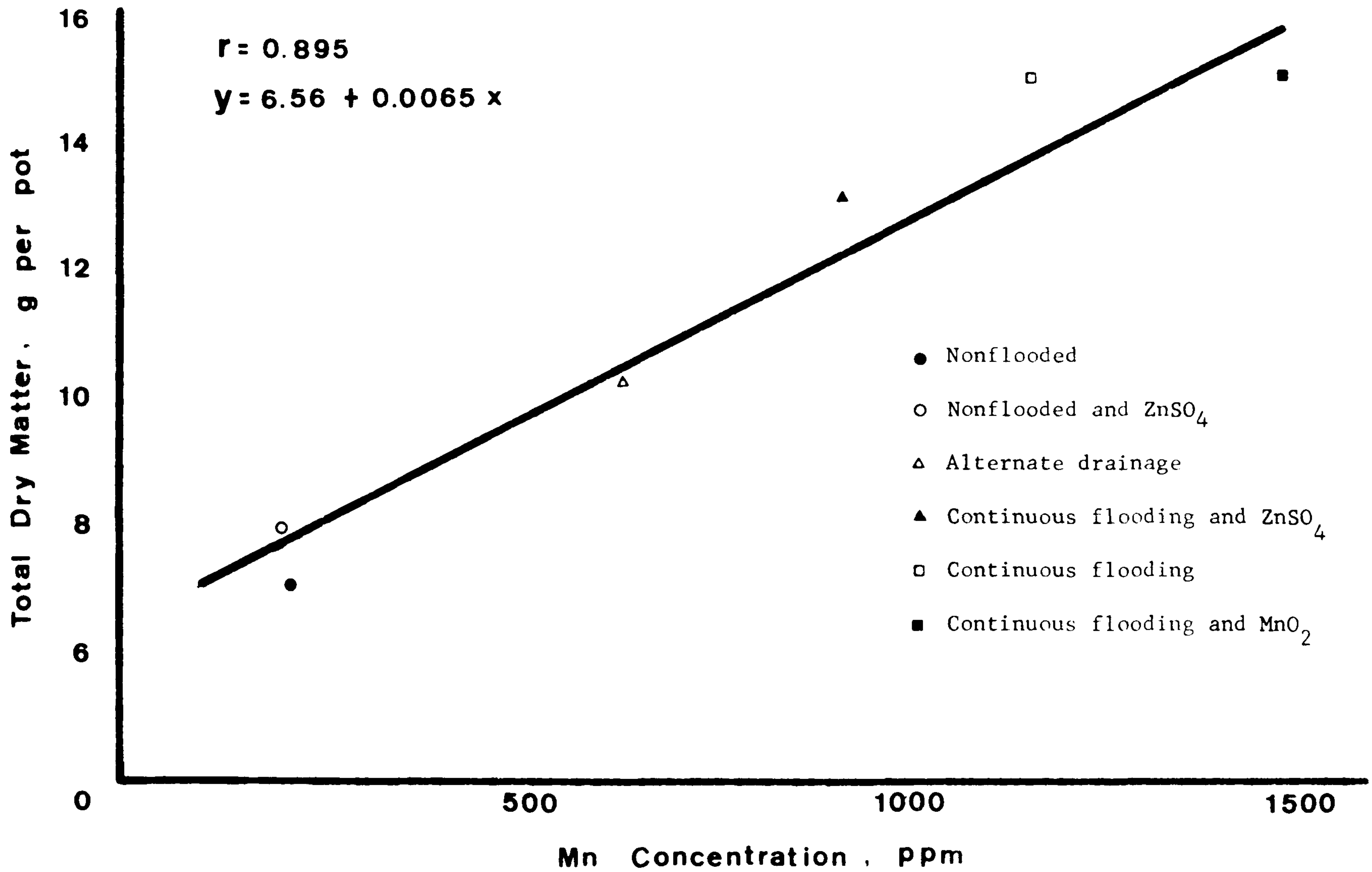

Figure 8. The relationship between the production of dry matter and the concentration of manganese in Saturn rice plants grown under different water, Zn, and Mn treatments.

assumption is further substantiated by the fact that a highly significant positive relationship between manganese uptake and the production of dry matter, r = 0.937, was obtained in the experiment.

It had been noted in a previous discussion of the data presented in Table 10 that under continuous flooding conditions, the application of zinc resulted in a significant decrease in the amount of dry matter produced by the rice plants. The influence of applications of zinc on the manganese to iron ratio has been discussed and offered as a possible explanation for the observed decrease in dry matter production. A second and closely related explanation for the observed decrease in the dry matter production is evident if the influence of applied zinc on the manganese concentration in the rice plants is considered. Under conditions of continuous flooding, the application of zinc resulted in a statistically significant reduction in both the concentration and the uptake of manganese by the rice plants. As previously stated, highly significant positive relationships between manganese concentration and dry matter production and between manganese uptake and dry matter produced by the rice plants were found. Therefore, it seems reasonable to assume that any factor which tended to reduce the concentration and/or the uptake of manganese by the rice plants would also tend to reduce the amount of dry matter produced. This would infer that the application of zinc, under continuous flooding conditions, resulted in a decrease in dry matter production because of the influence of zinc on the concentration and the uptake of manganese by the rice plants. Statistically significant negative relationships between zinc concentration and manganese concentration, r= -0.504, and between zinc concentration and manganese uptake, r = -0.475, were obtained in the experiment. This strengthens the feasibility of attempting to explain the reduction in dry matter production by the influence of zinc on the concentration and the uptake of manganese by the rice plants. However, no explanation can be offered as to why the application of zinc, under conditions of continuous flooding, resulted in a significant reduction in the concentration and uptake of manganese while on the nonflooded soil the application of zinc had no significant influence on either the concentration or the uptake of manganese by the rice plants.

The zinc concentration of the plants grown under conditions of continuous flooding was significantly lower than that of the plants grown on the nonflooded soil. Ishizuka and Ando (1968) reported that high levels of manganese tended to suppress zinc absorption by rice plants grown in nutrient solutions. The data presented in Table 10 and Figure 8 indicated that flooding increased the availability of manganese. It is possible that the increased availability of manganese interfered with the absorption of zinc with a resultant decrease in the concentration of zinc. However, this may be questionable since the total uptake of zinc by the rice plants was significantly increased when the plants were grown under flooded conditions. It may be that the zinc concentration in the rice plants grown under conditions of continuous flooding was lower because the production of dry matter was greater than that of the plants grown under nonflooded conditions.

The effects of applications of organic matter and zinc on the production of dry matter and on the concentration and the uptake of zinc, iron, and manganese by Saturn rice plants grown on Crowley silt loam, sample no. 21, under flooded conditions are presented in Table 12.

The data indicated that, when compared to the amount of dry matter produced by the plants grown on the untreated soil, the amount of dry matter produced was significantly reduced by the application of soybean leaves, rice straw, or cellulose. The application of rice straw resulted in a statistically significant decrease in dry matter production when compared to that produced when soybean leaves were applied. The application of cellulose resulted in a statistically significant decrease in dry matter production when compared to that produced where either rice straw or soybean leaves were applied. The amount of dry matter produced by the plants grown on soil that received an application of zinc was significantly greater than that produced by the plants of any other treatment. This suggested that the availability of indigenous zinc in the Crowley silt loam was at a critical level.

The application of soybean leaves resulted in a slight, but nonsignificant increase in the concentration of zinc in the rice plants when compared to the zinc concentration of the plants grown on the untreated soil. The application of rice straw and cellulose resulted in a nonsignificant decrease in the concentration of zinc in the rice plants. The concentration of zinc in the rice plants grown on soil that received an application of soybean leaves was

Table 12. The effects of applications of organic matter and zinc on the production of dry matter and on the concentration and the uptake of zinc, iron, and manganese by Saturn rice plants grown on Crowley silt loam under flooded conditions.

Treatment	Dry Matter	Concentration			Uptake		
		Zn	Fe	Mn	Zn	Fe	Mn
	g/pot	- - - - - ppm- - - - -			- - - - mg/pot- - - -		
Soybean leaves 1/	7.7	43	150	608	0.33	1.15	4.68
Rice straw 1/	7.1	34	114	232	0.24	0.81	1.65
Cellulose 1/	6.4	38	152	1377	0.24	0.97	8.82
Zinc 2/	10.5	111	156	489	1.16	1.64	5.13
Check	9.5	40	174	892	0.38	1.65	8.47
LSD, 5%	0.6	7	24	93	0.10	0.26	1.05

1/ Rates equivalent to 1% of the amount of soil per pot were added.

2/ Zinc was added as $ZnSO_4$ at a rate equivalent to 5 ppm Zn.

significantly greater than that of the plants grown on soil that had received an application of rice straw or cellulose. The application of zinc resulted in a highly significant increase in the concentration of zinc in the rice plants.

The uptake of zinc was significantly reduced by the application of rice straw or cellulose when compared to the uptake of zinc by the plants grown on the untreated soil. The application of soybean leaves did not significantly reduce the uptake of zinc. The differences between the uptake of zinc by the rice plants grown on soil that had received applications of soybean leaves, rice straw, or cellulose were not statistically significant. The application of zinc resulted in a highly significant increase in the uptake of zinc.

The lowest concentration of iron in the rice plants occurred in the plants grown on soil that received an application of rice straw. The concentration of iron in these plants was significantly lower than that of the plants grown on the untreated soil or on the soil that was treated with the other amendments. The concentration of iron in the plants grown on soil which had received an application of soybean leaves was significantly lower than that of the plants grown on untreated soil. The reduction in the concentration of iron in the rice plants grown on soil that received an application of cellulose was not statistically significant; however, the reduction approached statistical significance. The differences in the concentration of iron in the plants grown on soil that had received applications of soybean leaves or cellulose were not statistically significant. The application of zinc did not have a significant influence on the concentration of iron in the rice plants.

The uptake of iron by the rice plants grown on soil that received an application of rice straw or cellulose was significantly lower than that of the plants grown on soil that received an application of soybean leaves. When compared to the iron uptake by the plants grown on untreated soil, the iron uptake was significantly reduced by the application of soybean leaves. The application of zinc had no significant influence on the uptake of iron by the rice plants.

The lowest concentration of manganese occurred in the plants grown on soil that received an application of rice straw. The concentration of manganese in the plants grown on the soil that received rice straw was significantly lower than that of the plants grown on the soil treated with any of the other amendments or on the untreated soil. The concentration of manganese in the plants grown on soil that received an application of zinc was significantly lower than that of plants grown on the untreated soil or on soil that received an application of soybean leaves or cellulose. When compared to the concentration of manganese in the plants grown on untreated soil, the application of soybean leaves resulted in a significant reduction in the manganese concentration. The application of cellulose resulted in a highly significant increase in the concentration of manganese in the rice plants.

The uptake of manganese by the rice plants grown on the soil that received an application of rice straw was significantly lower than that of the plants grown on the untreated soil or on the soil treated with the other amendments. A significant difference was not obtained between the uptake of manganese by the plants grown on soil that received an application of zinc and the plants grown on soil that received an application of soybean leaves. However, the uptake of manganese by the plants grown on soil that received an application of zinc or soybeans was significantly lower than that of the plants grown on the untreated soil. When compared to the uptake of manganese by the rice plants grown on untreated soil, the application of cellulose did not have a significant influence on manganese uptake.

Research conducted at the International Rice Research Institute (1970) indicated that the application of organic matter to soils, which had a low zinc supplying capacity, resulted in a decrease in the dry matter production by rice plants. They observed that the application of organic matter resulted in a significant reduction in the concentration and uptake of zinc by the rice plants. They suggested that the influence of applications of organic matter on dry matter production was a result of the influence of organic matter on the availability of zinc.

Since the application of zinc resulted in a significant increase in the dry matter produced by the plants, it seems reasonable to assume that the availability of zinc in the Crowley silt loam, sample no. 21, used in the reported experiment was not at a level sufficient for optimum production of dry matter. The data presented in Table 12 indicated that, although the application of soybean leaves, rice straw, or cellulose to the Crowley silt loam did not significantly reduce the concentration of zinc in the plants, the application of rice straw or cellulose resulted in a significant reduction in the uptake of zinc. The application of soybean leaves did not significantly reduce the uptake of zinc. This raised the question of whether or not the application of organic matter had a direct influence on the "availability" of zinc. The fact that the application of rice straw or cellulose resulted in a significant decrease in the total uptake of zinc may be an indication that the "availability" of zinc was limited. However, there is a distinct possibility that the application of organic matter had an influence on plant growth other than its influence on the "availability" of zinc. Therefore, the reduction in the uptake of zinc, following the application of organic matter, may have been a result of a decrease in dry matter production caused by the influence of organic matter on a nutrient element other than zinc.

Using uptake as a criterion for evaluating "availability", the results indicated that with the exception of the influence of cellulose on manganese uptake, and the influence of soybean leaves on zinc uptake, the application of organic matter tended to reduce the "availability" of zinc, iron, and manganese. There are several suggestions that may be offered to explain the influence of organic matter. The stimulation of soil micro-organisms by the application of organic matter may have resulted in the immobilization of zinc, iron, and manganese to a level where their availability was limited. Biological decomposition of organic matter may have resulted in the formation of compounds capable of chelating or complexing zinc, iron, and manganese into forms that could not be absorbed or utilized by the rice plants. The formation of different types of compounds from the decomposition of soybean leaves, rice, straw, and cellulose may account for the variation in the influence of the application of these materials on the uptake of zinc, iron, and manganese. However, an explanation is not given as to why the application of cellulose tended to increase the uptake of manganese while the application of soybean leaves or rice straw resulted in a significant decrease in the uptake of manganese.

The effects of applications of zinc on the production of dry matter and on the concentration and the uptake of zinc, iron, and manganese by nine varieties of rice plants grown on Crowley silt loam, sample no. 21, under flooded conditions are presented in Table 13.

The data indicated that the application of zinc resulted in a significant increase in the amount of dry matter produced by the plants of the three short grain varieties, Taichung Native #1, Calusa, and Caloro. A significant increase in dry matter production, as a result of the application of zinc, by the plants of the medium grain varieties, Saturn and Vista, was also noted. The application of zinc resulted in a significant decrease in the amount of dry matter produced by the plants of the medium grade variety, IR-8. The application of zinc resulted in a significant increase in the production of

Table 13. The effects of applications of zinc on the production of dry matter and on the concentration and the uptake of zinc, iron, and manganese by nine varieties of rice plants grown on Crowley silt loam under flooded conditions.

Variety	Zn Treatment 1/	Dry Matter	Concentration Zn	Concentration Fe	Concentration Mn	Uptake Zn	Uptake Fe	Uptake Mn
		g/pot	- - - - ppm- - - -			- - - mg/pot- - -		
Short Grains								
Taichung Native #1	Zn	5.3	91	216	1006	0.48	1.14	5.33
	No Zn	4.8	28	224	1107	0.13	1.08	5.31
Calusa	Zn	5.6	98	197	1005	0.55	1.10	5.63
	No Zn	4.8	49	214	1141	0.23	1.03	5.48
Caloro	Zn	6.5	88	158	872	0.57	1.03	5.67
	No Zn	5.5	52	217	1103	0.28	1.19	6.07
Medium Grains								
Saturn	Zn	6.7	81	142	1074	0.54	0.95	7.20
	No Zn	5.3	48	164	1254	0.25	0.87	6.65
Vista	Zn	5.8	74	235	1158	0.43	1.36	6.72
	No Zn	4.4	40	209	1140	0.18	0.92	5.01
IR-8	Zn	4.9	88	278	296	0.43	1.36	1.45
	No Zn	5.4	46	150	985	0.25	0.81	5.32

(Continued)

Table 13 (Continued).

Variety	Zn Treatment 1/	Dry Matter	Concentration Zn	Fe	Mn	Uptake Zn	Fe	Mn
		g/pot	- - - - ppm- - - -			- - - mg/pot - - -		
Long Grains								
Bluebelle	Zn	4.6	84	185	786	0.39	0.85	3.62
	No Zn	5.0	43	186	1063	0.21	0.93	5.31
Starbonnet	Zn	3.8	109	552	459	0.42	2.10	1.74
	No Zn	4.5	40	215	487	0.18	0.97	2.19
Dawn	Zn	6.2	94	229	855	0.58	1.42	5.30
	No Zn	4.5	45	240	966	0.20	1.08	4.35
LSD, 5%		0.5	9	65	160	0.06	0.27	0.87

1/ Zinc was added as $ZnSO_4$ at a rate equivalent to 5 ppm of Zn.

dry matter by the plants of the long grain variety, Dawn. The production of dry matter by the plants of the long grain variety, Bluebelle, was not significantly affected by the application of zinc. The production of dry matter by the plants of the long grain variety, Starbonnet, was significantly reduced by the application of zinc.

The application of zinc resulted in a significant increase in the concentration and the uptake of zinc by the plants of all of the nine rice varieties. The highest concentration of zinc occurred in the Starbonnet plants that received an application of zinc. The lowest concentration of zinc occurred in the Taichung Native #1 plants that did not receive a supplement of zinc.

The iron concentration in all but the IR-8 plants and the Starbonnet plants, was not significantly affected by the application of zinc. The iron concentration in the IR-8 plants and the Starbonnet plants was significantly increased by the application of zinc. The application of zinc resulted in a significant increase in the uptake of iron by the plants of the IR-8, Vista, Starbonnet, and Dawn varieties. The uptake of iron by the plants of the other varieties tested was not significantly affected by the application of zinc.

The concentration of manganese in the plants of the Caloro, Saturn, IR-8, and Bluebelle varieties was significantly reduced by the application of zinc. The concentration of manganese in the plants of the other varieties tested was not significantly affected by the application of zinc. The uptake of manganese by the plants of the Vista and Dawn varieties was significantly increased by the application of zinc. The application of zinc resulted in a significant decrease in the uptake of manganese by the plants of the IR-8 and Bluebelle varieties. The application of zinc had no significant influence on the uptake of manganese by the Taichung Native #1, Calusa, Caloro, Saturn, and Starbonnet plants.

The application of zinc resulted in a significant decrease in the production of dry matter by the plants of the IR-8 and Starbonnet varieties. According to Tanaka, Loe, and Navasero (1966) and Yoshida et al. (1972), the possibility of iron toxicity in rice plants exists when the iron concentration is 300 ppm or greater. Interpretation of the data presented in Table 13 suggested that the application of zinc may have resulted in an increase in the concentration of iron in the plants of the IR-8 and Starbonnet varieties to a toxic level.

The iron concentration in the Starbonnet plants was increased from 215 to 552 ppm by the application of zinc. This indicated that the concentration of iron in the plants of the Starbonnet variety, grown on soil that received an application of zinc was at a toxic level. The iron concentration in the plants of the IR-8 variety was increased from 150 to 278 ppm by the application of zinc. Although the iron concentration in the plants of the IR-8 variety was below the assumed toxicity level of 300 ppm, it is possible that the concentration of 278 ppm of iron was approaching toxicity and tended to depress the production of dry matter. The influence of applications of zinc on dry matter production by the plants of the IR-8 and Starbonnet varieties may be explained by the influence of zinc on iron concentration.

A statistically significant negative relationship, r = -0.533, was calculated between iron concentration and the production of dry matter. This further substantiated the supposition that iron toxicity may have been at least partially responsible for the decrease in the dry matter production by the plants of the IR-8 and Starbonnet varieties grown on soil that received applications of zinc.

The effects of applications of zinc on the production of dry matter and on the concentration of manganese and iron and the manganese to iron ratio of nine varieties of rice plants grown on Crowley silt loam under flooded conditions are presented in Table 14.

The data indicated that the application of zinc resulted in a considerable reduction in the manganese to iron ratios of the plants of the IR-8 and Starbonnet varieties. The manganese to iron ratio of the IR-8 plants was reduced from 6.6 to 1.1 by the application of zinc. The manganese to iron ratio of the plants of the Starbonnet variety was reduced from 2.3 to 0.8 by the application of zinc. This constituted a reduction of 83% and 65%, respectively, in the manganese to iron ratios. The manganese to iron ratios of the plants of the other varieties tested were reduced less than 20% by the application of zinc. The manganese to iron ratio was slightly increased in the plants of the Caloro variety following an application of zinc.

The influence of the application of zinc on the manganese to iron ratio may have been responsible for the reduction in the amount of dry matter produced by the plants of the IR-8 and Starbonnet varieties grown on soil that received an application of zinc. The iron concentration in the plants of the two varieties was significantly increased

Table 14. The effects of applications of zinc on the production of dry matter and on the concentrations of manganese and iron and the manganese to iron ratio of nine varieties of rice plants grown on Crowley silt loam under flooded conditions.

Variety	Zn 1/ Treatment	Dry Matter	Concentration Mn	Concentration Fe	Mn:Fe Ratio
		g/pot	- -ppm- -		
Short Grains					
Taichung Native #1	Zn	5.3	1006	216	4.7
	No Zn	4.8	1107	224	4.9
Calusa	Zn	5.6	1005	197	5.1
	No Zn	4.8	1141	214	5.3
Caloro	Zn	6.5	872	158	5.5
	No Zn	5.5	1103	217	5.1
Medium Grains					
Saturn	Zn	6.7	1074	142	7.6
	No Zn	5.3	1254	164	7.7
Vista	Zn	5.8	1158	235	4.9
	No Zn	4.4	1140	209	5.5
IR-8	Zn	4.9	296	278	1.1
	No Zn	5.4	985	150	6.6
Long Grains					
Bluebelle	Zn	4.6	786	185	4.3
	No Zn	5.0	1063	186	5.7
Starbonnet	Zn	3.8	459	552	0.8
	No Zn	4.5	487	215	2.3
Dawn	Zn	6.2	855	229	3.7
	No Zn	4.5	966	240	4.0

1/ Zinc was added as $ZnSO_4$ at a rate equivalent to 5 ppm of Zn.

by the application of zinc. The manganese concentration in the plants of the IR-8 variety was significantly decreased by the application of zinc. This resulted in a much narrower manganese to iron ratio than that of the plants of the other varieties grown on soil that received an application of zinc.

The effects of applications of zinc on the production of dry matter and on the concentration and the uptake of phosphorus by nine varieties of rice plants grown on Crowley silt loam under flooded conditions are presented in Table 15.

The data indicated that the influence of applications of zinc on the concentration and uptake of phosphorus depended on the rice variety. The application of zinc significantly increased the concentration of phosphorus in the plants of the Caloro, Vista, and Dawn varieties of rice. The application of zinc did not have a significant influence on the concentration of phosphorus in the Taichung Native #1, Calusa, and Saturn plants. The phosphorus concentration in the IR-8, Bluebelle, and Starbonnet plants was significantly reduced by the application of zinc. The uptake of phosphorus by the plants of the Taichung Native #1, Calusa, and Bluebelle varieties was not significantly affected by the application of zinc. The application of zinc resulted in a significant increase in the uptake of phosphorus by the Caloro, Saturn, Vista, and Dawn plants. A significant decrease in the uptake of phosphorus by the plants of the IR-8 and Starbonnet varieties was noted.

Table 15. The effects of applications of zinc on the production of dry matter and on the concentration and the uptake of phosphorus by nine varieties of rice plants grown on Crowley silt loam under flooded conditions.

Variety	Zn 1/ Treatment	Dry Matter	Phosphorus Concentration	Phosphorus Uptake
		g/pot	ppm	mg/pot
Short Grains				
Taichung Native #1	Zn	5.3	2116	11.21
	No Zn	4.8	2313	11.10
Calusa	Zn	5.6	2250	12.60
	No Zn	4.8	2018	9.69
Caloro	Zn	6.5	3875	25.19
	No Zn	5.5	2500	13.75
Medium Grains				
Saturn	Zn	6.7	2695	18.06
	No Zn	5.3	2563	13.58
Vista	Zn	5.8	2683	15.56
	No Zn	4.4	2188	9.63
IR-8	Zn	4.9	1500	7.35
	No Zn	5.4	2188	11.82
Long Grains				
Bluebelle	Zn	4.6	1629	7.49
	No Zn	5.0	2125	10.63
Starbonnet	Zn	3.8	938	3.56
	No Zn	4.5	2106	9.48
Dawn	Zn	6.2	2507	15.54
	No Zn	4.5	2021	9.10
LSD, 5%		0.5	474	4.13

1/ Zinc was added as $ZnSO_4$ at a rate equivalent to 5 ppm of Zn.

In each case where the application of zinc resulted in a significant reduction in the phosphorus concentration, the production of dry matter was also reduced. However, the reduction in dry matter production by the plants of the Bluebelle variety was not statistically significant. Therefore, the influence of applications of zinc on the concentration of phosphorus may offer an explanation for the influence of applied zinc on dry matter production. The influence of zinc on the phosphorus concentration may have been of particular significance in the case of the plants of the Starbonnet variety. The phosphorus concentration was reduced from 2106 ppm to 938 ppm by the application of zinc. According to Chapman (1966), a concentration of 1000 ppm of phosphorus is considered critical and it is below a sufficient level for optimum growth of rice.

The effects of applications of zinc on the production of dry matter and on the concentration and the uptake of zinc, iron, and manganese by Saturn rice plants grown on selected soils under flooded conditions are presented in Table 16.

The data indicated that the application of zinc to the Hebert silt loam, sample no. 4, Norwood silt loam, sample no. 8, and Shubuta fine sandy loam, sample no. 13, resulted in a statistically significant increase in the amount of dry matter produced by the rice plants grown on these soils. The 0.1 N HCl extractable zinc content of the three soils was 1.6, 2.9, and 2.0 ppm, respectively. Evaluation and comparison of the chemical analysis of the three soils did not offer any apparent explanation for the increase in dry matter production obtained

Table 16. The effects of applications of zinc on the production of dry matter and on the concentration and the uptake of zinc, iron, and manganese by Saturn rice plants grown on selected soils under flooded conditions.

Sample Number	Soil Type	Treatment 1/	Dry Matter	Concentration Zn	Concentration Fe	Concentration Mn	Uptake Zn	Uptake Fe	Uptake Mn
			g/pot	- - - ppm - - -			- - -mg/pot- - -		
- - - Mississippi River Alluvial Soils- - -									
1	Mhoon sicl	Zn	19.7	59	183	1223	1.16	3.61	24.08
		No Zn	19.8	52	163	1133	1.02	3.23	22.43
- - - Alluvial Soils of the Ouachita & Arkansas Rivers- - -									
2	Gallion sil	Zn	9.5	41	250	793	0.39	2.37	7.53
		No Zn	10.6	23	286	961	0.24	3.03	10.19
3	Hebert sil	Zn	12.0	52	242	646	0.62	2.90	7.75
		No Zn	13.0	35	285	931	0.46	3.70	12.10
4	Hebert sil	Zn	6.1	102	239	1458	0.62	1.46	8.90
		No Zn	2.8	49	213	1048	0.14	0.60	2.94
5	Hebert sil	Zn	14.6	69	193	2293	1.00	2.82	33.47
		No Zn	15.7	48	231	2360	0.76	3.63	37.05
- - - Alluvial Soils of the Red River - - -									
6	Pulaski vfsl	Zn	9.3	36	192	2075	0.33	1.79	19.30
		No Zn	9.0	25	166	2192	0.23	1.50	19.73
7	Norwood sil	Zn	1.6	97	394	273	0.16	0.63	0.44
		No Zn	1.0	58	321	277	0.06	0.32	0.28

(Continued)

Table 16 (Continued).

Sample Number	Soil Type	Treatment 1/	Dry Matter	Concentration Zn	Concentration Fe	Concentration Mg	Uptake Zn	Uptake Fe	Uptake Mn
			g/pot	- - -	ppm-	- -	- - -	mg/pot-	- - -
8	Norwood sil	Zn	13.2	37	188	447	0.49	2.48	5.90
		No Zn	8.8	24	158	747	0.21	1.39	6.57
9	Norwood sil	Zn	1.2	110	512	163	0.13	0.61	0.20
		No Zn	1.2	62	351	185	0.07	0.42	0.22
10	Yahola vfsl	Zn	11.2	49	182	834	0.54	2.04	9.34
		No Zn	10.6	37	126	865	0.39	1.33	9.17
11	Yahola vfsl	Zn	9.5	65	159	777	0.61	1.51	7.39
		No Zn	8.2	44	143	589	0.36	1.17	4.84
- - - - - - - - - - - - - - - - - - - Coastal Plains & Flatwoods Soils- - - - - - - - - - - - - - - - - - -									
12	Bowie fsl	Zn	11.2	85	178	731	0.95	1.99	8.19
		No Zn	10.8	64	237	793	0.69	2.56	8.57
13	Shubuta fsl	Zn	14.1	74	261	1472	1.04	3.68	20.75
		No Zn	10.5	43	180	1604	0.45	1.89	16.84
14	Ruston fsl	Zn	5.6	105	269	832	0.59	1.51	4.66
		No Zn	4.4	62	188	1044	0.27	0.83	4.60
- - - - - - - - - - - - - - - - - - - Soils of the Coastal Prairies - - - - - - - - - - - - - - - - - - -									
15	Acadia sil	Zn	3.5	114	286	243	0.40	1.00	0.85
		No Zn	3.5	45	280	343	0.16	0.98	1.20

(Continued)

Table 16 (Continued).

Sample Number	Soil Type	Treatment 1/	Dry Matter	Concentration Zn	Fe	Mn	Uptake Zn	Fe	Mn
			g/pot	- - - ppm- - -			- - -mg/pot- - -		
16	Acadia sil	Zn	18.3	98	223	2655	1.80	4.07	48.58
		No Zn	17.5	82	172	2607	1.43	3.01	45.65
17	Crowley sil	Zn	10.7	96	192	913	1.02	2.06	9.77
		No Zn	11.4	37	321	771	0.42	3.66	8.79
18	Crowley sil	Zn	11.1	91	152	861	1.01	1.69	9.56
		No Zn	10.5	33	198	985	0.34	2.08	10.35
19	Crowley sil	Zn	6.7	56	150	481	0.37	1.01	3.22
		No Zn	6.9	48	184	438	0.33	1.27	3.03
20	Crowley sil	Zn	2.4	68	193	553	0.16	0.46	1.33
		No Zn	2.1	47	183	544	0.10	0.39	1.14
21	Crowley sil	Zn	10.6	114	160	487	1.21	1.70	5.16
		No Zn	9.5	39	179	851	0.37	1.70	8.08
22	Morey sil	Zn	10.6	69	230	437	0.73	2.44	4.63
		No Zn	13.1	47	201	505	0.62	2.63	6.62
23	Mowata sil	Zn	11.9	50	191	1414	0.60	2.27	16.82
		No Zn	11.5	38	162	1233	0.44	1.76	14.18
24	Bernard cl	Zn	7.0	77	235	484	0.54	1.65	3.39
		No Zn	6.8	56	218	433	0.38	1.48	2.94

(Continued)

Table 16 (Continued).

Sample Number	Soil Type	Treatment 1/	Dry Matter	Concentration Zn	Concentration Fe	Concentration Mn	Uptake Zn	Uptake Fe	Uptake Mn
			g/pot	- - - -ppm- - - -			- - -mg/pot- - -		
- - - Mississippi Terraces & Loessial Hills Soils- - -									
25	Patoutville sil	Zn	11.3	94	194	1242	1.06	2.20	14.03
		No Zn	12.3	60	184	1513	0.74	2.27	18.61
26	Patoutville sil	Zn	12.0	134	209	4082	1.60	2.51	48.99
		No Zn	12.4	74	269	3877	0.91	3.33	48.07
27	Patoutville sil	Zn	4.4	54	125	329	0.24	0.55	1.45
		No Zn	3.4	43	105	503	0.15	0.36	1.71
28	Jeanerette sil	Zn	10.4	54	227	471	0.57	2.36	4.90
		No Zn	13.0	38	257	520	0.50	3.35	6.76
29	Jeanerette sil	Zn	11.0	73	217	764	0.80	2.39	8.40
		No Zn	12.5	52	208	676	0.66	2.60	8.45
LSD, 5%			2.2	13	66	NS	0.16	0.80	NS

1/ Zinc was added as $ZnSO_4$ at a rate equivalent to 5 ppm of Zn.

from the application of zinc. There were six soils, other than the Hebert silt loam, sample no. 4, with an acid extractable zinc content of 1.6 ppm or less. The application of zinc did not result in a significant increase in the dry matter production by the rice plants grown on these soils. The data indicated that under the conditions of this experiment, the use of the dilute acid extractable zinc content of the soil alone is not a sufficient criterion for predicting a response to application of zinc.

The application of zinc resulted in a significant decrease in the amount of dry matter produced by the rice plants grown on the Morey silt loam, sample no. 22, and the Jeanerette silt loam, sample no. 28. The acid extractable zinc content of the Morey silt loam was 1.9 ppm. The acid extractable zinc content of the Jeanerette silt loam was 3.9 ppm. Evaluation and comparison of the chemical analysis of the two soils did not offer an explanation for the influence of applications of zinc on the amount of dry matter produced by the rice plants.

The concentration of zinc in the plants grown on the Morey silt loam was increased from 47 to 69 ppm by the application of zinc. The zinc concentration of the rice plants grown on the Jeanerette silt loam was increased from 38 to 54 ppm. The possibility of zinc toxicity of the rice plants, as a result of the application of zinc, was eliminated as a cause of the decrease in dry matter production since a greater zinc concentration in rice plants grown on some of the other soils was associated with larger amounts of dry matter produced than that produced on either the Morey or the Jeanerette silt loam.

The application of zinc resulted in nonsignificant increases in the amount of dry matter produced by the rice plants grown on 13 of the 29 soils. Nonsignificant decreases in dry matter production following application of zinc were noted on 9 of the 29 soils. The application of zinc had no effect on the amount of dry matter produced by the rice plants grown on the Norwood silt loam, sample no. 9, and the Acadia silt loam, sample no. 15.

The application of zinc resulted in statistically significant increases in the zinc concentrations in the rice plants grown on 23 of the 29 soils included in the experiment. Nonsignificant increases in the zinc concentrations in the plants grown on 6 of the 29 soils were noted. Where zinc was not applied, the zinc concentrations ranged from a low of 24 ppm in the plants grown on the Norwood silt loam, sample no. 8, to a high of 82 ppm in the plants grown on the Acadia silt loam, sample no. 16. Where zinc was applied, the zinc concentrations ranged from a low of 36 ppm in the plants grown on the Pulaski very fine sandy loam, sample no. 6, to a high of 134 ppm in the plants grown on the Patoutville silt loam, sample no. 26.

The application of zinc resulted in statistically significant increases in the uptake of zinc by the rice plants grown on 17 of the 29 soils. Nonsignificant increases in the uptake of zinc by the rice plants grown on 12 of the 29 soils were noted.

The application of zinc to the Norwood silt loams, samples no. 7 and 9, Ruston fine sandy loam, and Shubuta fine sandy loam resulted in significant increases in the concentrations of the iron in the rice plants grown on these soils. The concentration of iron in the plants grown on the Crowley silt loam, sample no. 17, was significantly decreased by the application of zinc. The application of zinc resulted in a nonsignificant increase in the concentrations of iron in the rice plants grown on 15 of the 29 soils. Nonsignificant decreases in the iron concentrations in the plants grown on 9 of the 29 soils were noted. Where zinc was not applied, the iron concentrations ranged from a low of 105 ppm in the rice plants grown on the Patoutville silt loam, sample no. 27, to a high of 351 ppm in the plants grown on the Norwood silt loam, sample no. 9. Where zinc was applied, the iron concentrations ranged from a low of 125 ppm in the plants grown on the Patoutville silt loam, sample no. 27, to a high of 512 ppm in the plants grown on the Norwood silt loam, sample no. 9.

The application of zinc to the Hebert silt loam, sample no. 4, Norwood silt loam, sample no. 8, Shubuta fine sandy loam, sample no. 13, and Acadia silt loam, sample no. 16, resulted in statistically significant increases in the uptake of iron by the rice plants grown on these soils. The uptake of iron by the Hebert silt loams, samples no. 3 and 5, Crowley silt loam, sample no. 17, Patoutville silt loam, sample no. 26, was significantly reduced by the application of zinc. Nonsignificant increases in the uptake of iron by plants grown on 12 of the 29 soils was observed. Nonsignificant decreases in the uptake of iron by the plants on 7 of the 29 soils were noted. The application of zinc did not have a measurable influence on the uptake of iron by the plants grown on the Crowley silt loam, sample no. 21.

A statistically significant interaction did not occur between soils and zinc treatments on either the concentration or the uptake of manganese by the plants. The application of zinc to some of the soils resulted in substantial differences in both the concentration and the uptake of manganese by the rice plants. However, the influence of applications of zinc on either the concentration or the uptake of manganese was not statistically significant. This was probably due to a large amount of variation between replications of individual treatments. In the statistical analysis of the manganese concentration and uptake data, the variation between replications resulted in a relatively large experimental error. The F value obtained for the influence of zinc treatments on the concentration and the uptake of manganese was not statistically significant.

The manganese concentration was increased, following the application of zinc, in the rice plants grown on 11 of the 29 soils. The concentration of manganese was reduced, by the application of zinc, in the plants grown on 19 of the 29 soils. Where zinc was not applied, the manganese concentrations ranged from a low of 185 ppm in the plants grown on the Norwood silt loam, sample no. 9, to a high of 3877 ppm in the plants grown on the Patoutville silt loam, sample no. 26. Where zinc was applied the manganese concentrations ranged from a low of 163 ppm in the plants grown on the Norwood silt loam, sample no. 9, to a high of 4082 ppm in the plants grown on the Patoutville silt loam, sample no. 26. The application of zinc resulted in nonsignificant decreases in the uptake of manganese by the rice plants grown on 15 of the 29 soils.

The correlation coefficients showing the relationships between the contents of extractable zinc, iron, and manganese in the soils, and the production of dry matter and the concentration and uptake of zinc, iron, and manganese by Saturn rice plants grown under flooded conditions, with and without applied zinc, on selected soils in Louisiana are presented in Table 17.

The data indicated that the relationships between 0.1 N HCl extractable zinc content of the soil, and the dry matter production, the concentration of zinc, iron, or manganese, and the uptake of zinc, iron, or manganese by the rice plants were not statistically significant. The fact that extractable zinc was not significantly related to either the concentration or the uptake of zinc lends further evidence to support the conclusion, made previously, that dilute acid extractable zinc is not a sufficient criterion for predicting the response to applications of zinc by rice plants grown under conditions similar to that of the reported experiment.

The relationships between 1 N sodium acetate extractable iron in the soil, and the production of dry matter, the concentrations of zinc, iron, or manganese, and the uptake of zinc, iron, or manganese, by the rice plants were not statistically significant.

Irrespective of the zinc treatment, the 1 N sodium acetate extractable manganese content of the soil was not significantly related to the concentration of zinc, the concentration of iron, or the uptake of iron by the rice plants. When zinc was applied, statistically significant relationships were calculated between extractable manganese

Table 17.-Correlation coefficients showing the relationships between the extractable contents of zinc, iron, and manganese in the soils, and the dry matter production and the concentration and uptake of zinc, iron, and manganese by Saturn rice plants grown under flooded conditions, with and without applied zinc, on selected soils in Louisiana.

Extractable nutrient	Dry matter	Concentration			Uptake		
		Zn	Fe	Mn	Zn	Fe	Mn
---No Zinc Applied---							
Zn[1/]	0.315	0.109	-0.140	0.140	0.283	0.192	0.291
Fe[2/]	0.143	0.013	0.094	0.155	0.112	0.228	0.152
Mn[2/]	0.461*	0.104	-0.153	0.664**	0.460*	0.337	0.677**
---Zinc Applied[3/]---							
Zn[1/]	0.306	-0.277	-0.118	0.198	0.146	0.336	0.333
Fe[2/]	0.094	-0.183	-0.100	0.155	0.021	0.141	0.124
Mn[2/]	0.455*	-0.075	-0.287	0.695**	0.406*	0.374	0.685**

*Significant at the 5% level.
**Significant at the 1% level.

[1/]Extracted with 0.1 N HCl.
[2/]Extracted with 1 N sodium acetate, adjusted to pH 4.5.
[3/]Zinc was added as $ZnSO_4$ at a rate equivalent to 5 ppm of Zn.

and dry matter production, r = 0.455, zinc uptake, r = 0.406, manganese concentration, r = 0.695, and manganese uptake, r = 0.685. When zinc was not applied, significant relationships existed between extractable manganese and dry matter production, r = 0.461, zinc uptake, r = 0.460, manganese concentration, r = 0.664, and manganese uptake, r = 0.677, by the rice plants.

SUMMARY AND CONCLUSIONS

Six experiments were conducted in the greenhouse to study the effects of flooding and applications of zinc, lime, and organic matter on the production of dry matter and on the concentration and the uptake of zinc, iron, and manganese by rice (Oryza sativa L.) plants grown for eight weeks on selected soils in Louisiana.

In general, the production of dry matter by the rice plants grown on flooded soil was greater than the production of dry matter by plants grown on nonflooded soil. In instances where flooding resulted in an increase in dry matter production, the increase was attributed to factors such as the increased rate of tillering by the plants, the increased "availability" of phosphorus, and the increased "availability" of manganese to the rice plants grown on flooded soil.

When lime was applied, the influence of flooding on the concentration of zinc in the rice plants depended on the rate of lime applied. Flooding the Patoutville silt loam that received 2, 3, and 4 tons of lime per acre resulted in an increase in the concentration of zinc in the plants. Flooding the unlimed soils and the Patoutville silt loam that received 1 ton of lime per acre generally resulted in a decrease in the concentration of zinc in the rice plants.

In most instances, flooding the soils resulted in a reduction in the zinc concentration of zinc in the plants. However, the uptake of zinc was not significantly reduced.

Flooding the soils resulted in a significant increase in the concentration of iron in the rice plants. With one exception, flooding resulted in a significant increase in the uptake of iron.

Flooding resulted in an increase in the concentration of manganese in the rice plants grown on all the unlimed soils and the Patoutville silt loam that received 1 and 2 tons of lime per acre. When lime and zinc were applied, the influence of flooding the soil on the concentration of manganese in the plants depended on the lime and the zinc treatments. Flooding the Patoutville silt loam that received 3 and 4 tons of lime per acre and supplementary zinc resulted in a significant decrease in the concentration of manganese in the plants.

The influence of applications of zinc on the production of dry matter depended on factors such as the water and the lime treatments, the variety of rice, and the soil. The influence of applied zinc varied from a statistically significant increase to a statistically significant decrease in dry matter production.

In the experiment conducted to study the influence of flooding, zinc, and lime on rice grown on Patoutville silt loam, the influence of applied zinc on the production of dry matter depended on the lime and the flooding treatments. The application of zinc to the unlimed soil and the soil that received 1 and 2 tons of lime per acre resulted in an increase in dry matter production. On the Patoutville silt loam that received 3 and 4 tons of lime, the influenced of applied zinc varied from a nonsignificant increase to a significant decrease in the production of dry matter.

An experiment was conducted to study the influence of different water treatments and applications of zinc and manganese dioxide on rice grown on Crowley silt loam. The application of zinc resulted in a significant decrease in the production of dry matter by the rice plants grown on the continuously flooded soil. The application of zinc to the nonflooded Crowley silt loam resulted in a nonsignificant increase in the production of dry matter.

In the experiment conducted to study varietal response to applications of zinc, the influence of applied zinc varied from a significant increase to a significant decrease in the dry matter production by the rice plants. The application of zinc to the Crowley silt loam resulted in a significant increase in the amount of dry matter produced by the plants of the Taichung Native # 1, Calusa, Caloro, Saturn, Vista, and Dawn varieties of rice. The dry matter production by the plants of the IR-8 and Starbonnet varieties was significantly reduced by the application of zinc. The dry matter production by the plants of the Bluebelle variety was not significantly affected. The influence of applied zinc on the manganese to iron ratio, the possibility of zinc-induced phosphorus deficiency, and the possibility of zinc-induced iron toxicity were offered as explanations for the decrease in the dry matter production by the plants of the IR-8 and Starbonnet varieties.

The application of zinc to 29 soils resulted in a significant increase in the dry matter produced by the rice plants grown on three of the soils. The application of zinc resulted in a significant decrease in the dry matter produced by plants grown on two of the soils.

The application of zinc resulted in an increase in the concentration and the uptake of zinc by rice plants. However, not all of the increases were statistically significant.

The 0.1 N HCl extractable zinc content of the soils was not related to either the concentration or the uptake of zinc by rice plants grown under flooded conditions. This suggested that the use of 0.1 HCl extractable zinc does not provide a reliable index of the "availability" of zinc to rice plants grown for eight weeks on flooded soil in the greenhouse.

The influence of applications of zinc on the concentration and the uptake of iron and manganese by rice plants varied from a significant increase to a significant decrease. The data indicated that zinc-iron and zinc-manganese interactions occurred. The nature of the interactions depended on factors such as the water and lime treatments, the variety of rice, and the soil.

The application of 1, 2, 3, and 4 tons of lime per acre to a Patoutville silt loam resulted in a decrease in the dry matter production and the concentration and the uptake of zinc by rice plants. The decrease in dry matter production could not be attributed solely to the influence of lime on the concentration and uptake of zinc. The application of zinc at the 1, 2, 3, and 4 ton rates of lime did not promote the growth of rice plants to the level attained by the plants grown on the unlimed soil.

The influence of applications of lime to a Patoutville silt loam on the concentration of iron in rice plants depended on the flooding and the zinc treatments. Under flooded conditions with and without added zinc, the application of 1 ton of lime resulted in an significant increase in the concentration of iron in the rice plants. The application of 2, 3, and 4 tons of lime per acre did not result in a further significant increase in the concentration of iron in the plants. Under non-flooded conditions, the application of 1 ton of lime per acre resulted in a significant decrease in the concentration of iron in the plants grown on the soil that received an application of zinc. The application of 2, 3, and 4 tons of lime did not result in a further significant reduction in the concentration of iron. Under nonflooded conditions and when zinc was not applied, the application of 1, 2, 3, and 4 tons of lime per acre resulted in a progressive decrease in the concentration of iron in the plants.

The application of 1, 2, 3, and 4 tons of lime to a Patoutville silt loam resulted in a progressive decrease in the uptake of iron by rice plants grown under both flooded and nonflooded conditions with and without the addition of zinc.

The influence of applications of lime on the concentration and uptake of manganese depended on the rate of lime applied. Increasing the rate of lime from 0 to 1 and 2 tons per acre resulted in a progressive decrease in the concentration and the uptake of manganese by rice plants grown on Patoutville silt loam. However, when the soil reaction was adjusted to pH 6.5 and pH 6.9 following the application of 3 and 4 tons of lime per acre, the concentration and the uptake of manganese were significantly increased. The results suggested that adjusting the soil reaction of the Patoutville silt loam from pH 6.0 to pH 6.5 and pH 6.9 increased the "availability" of manganese to the rice plants.

The application of soybean leaves, rice straw, and cellulose to a Crowley silt loam resulted in a significant decrease in the amount of dry matter produced by rice plants grown under flooded soil conditions. The concentration of zinc in the rice plants was not significantly reduced by the application of soybean leaves, rice straw, and cellulose. The uptake of zinc was significantly reduced by the application of rice straw and cellulose. The reduction in the uptake of zinc as a result of the application of soybean leaves was not statistically significant. The concentration and the uptake of iron were reduced by the application of organic matter. However, the reduction in the concentration of iron in the plants as a result of the addition of cellulose was not statistically significant. The concentration and the uptake of manganese by the rice plants were significantly reduced by the application of soybean leaves and rice straw. The concentration, but not the uptake, of manganese was significantly increased by the application of cellulose. The reduction in the uptake of zinc, iron, and manganese as a result of the application of organic matter was attributed to possible microbial immobilization and complexing of zinc, iron, and manganese by compounds formed in the decomposition of organic matter.

LITERATURE CITED

Adriano, D. C., and L. S. Murphy. 1970. Effects of ammonium polyphosphates on yield and chemical composition of irrigated corn. Agron. J. 62:561-567.

Adriano, D. C., G. M. Paulsen, and L. S. Murphy. 1971. Phosphorus-iron and phosphorus-zinc relationships in corn (Zea mays L.) seedlings as affected by mineral nutrition. Agron. J. 63:36-39.

Ambler, J. E., J. C. Brown, and H. G. Gauch. 1970. Effect of zinc on translocation of iron in soybean plants. Plant Physiol. 46:320-323.

Bauer, A., and W. L. Lindsay. 1965. The effect of soil temperature on the availability of indigenous soil zinc. Soil Sci. Soc. Amer. Proc. 29:413-416.

Baughman, N. M. 1965. The effect of organic matter on the retention of zinc by soil. Agron. J. 57:523-525.

Bingham, F. T. 1963. Relation between phosphorus and micronutrients in plants. Soil Sci. Soc. Amer. Proc. 27:389-390.

Boawn, L. C., F. G. Viets, Jr., C. L. Crawford, and J. L. Nelson. 1960. Effect of nitrogen carrier, nitrogen rate, zinc rate, and pH on zinc uptake by sorghum, potatoes, and sugar beets. Soil Sci. 90:329-337.

Bowen, J. E. 1969. Absorption of copper, zinc, and manganese by sugar cane tissue. Plant Physiol. 44:225-261.

Brown, J. C., J. E. Ambler, R. L. Chaney, and C. D. Foy. 1972. Differential responses of genotypes to micronutrients. p. 389-418. In Micronutrients in agriculture. Soil Sci. Soc. Amer. Madison, Wisconsin.

Brown, J. C., R. S. Holmes, and L. O. Tiffin. 1961. Iron chlorosis in soybeans as related to the genotype of rootstock: 3. Chlorosis susceptibility and reductive capacity at the root. Soil Sci. 91:127-132.

Brown, A. L., and J. J. Jurinak. 1964. Effect of liming on availability of zinc and copper. Soil Sci. 93:170-173.

Brown, A. L., and B. A. Krantz. 1961. Zinc deficiency diagnosis through soil analysis. California Agr. 15:15.

Brupbacher, R. H., W. P. Bonner, and J. E. Sedberry, Jr. 1968. Analytical methods and procedures used in the soil testing laboratory. Louisiana Agr. Exp. Sta. Bull. 632.

Burleson, C. A., A. D. Dacus, and C. J. Gerard. 1961. The effect of phosphorus fertilization on the zinc nutrition of several irrigated crops. Soil Sci. Soc. Amer. Proc. 25:365-368.

Burleson, C. A., and N. R. Page. 1967. Phosphorus and zinc interactions in flax. Soil Sci. Soc. Amer. Proc. 31:510-511.

Camp, A. W. 1945. Zinc as a nutrient in plant growth. Soil Sci. 60: 157-164.

Chandler, W. H. 1937. Zinc as a nutrient for plants. Bot. Gaz. 98: 625-646.

Chaney, R. L., J. C. Brown, and L. O. Tiffin. 1972. Obligatory reduction of ferric chelates in iron uptake by soybeans. Plant Physiol. 49:106-111.

Chapman, H. D. 1966. Diagnostic criteria for plants and soils. Univ. of California, Div. of Agri. Sciences, Riverside, California.

Chapman, H. D., A. P. Vanselow, and G. F. Liebig, Jr. 1937. The production of citrus mottle-leaf in controlled nutrient culture. J. Agr. Res. 55:365-366.

Chaudhry, M. S., and E. O. McLean. 1963. Comparative effects of flooded and unflooded soil conditions and nitrogen application on growth and nutrient uptake by rice plants. Agron. J. 55:565-567.

Cherian, E. C., G. M. Paulsen, and L. S. Murphy. 1968. Nutrient uptake of lowland rice under flooded and nonflooded soil conditions. Agron. J. 60:554-557.

Clark, F., D. C. Nearpass, and A. W. Specht. 1957. Influence of organic additions and flooding on iron and manganese uptake by rice. Agron. J. 49:586-589.

Cralley, E. M., and C. R. Adair. 1943. Effect of irrigation treatment on stem rot severity, plant development, yield, and quality of rice. J. Amer. Soc. Agron. 35:499-507.

DeNumbrum, L. E., and M. L. Jackson. 1956. Infrared absorption evidence on exchange reaction mechanism of copper and zinc with layer silicate clays and peat. Soil Sci. Soc. Amer. Proc. 20:334-337.

DeRemer, E. D., and R. L. Smith. 1964. A preliminary study on the nature of a zinc deficiency in field beans as determined by radioactive zinc. Agron. J. 56:67-70.

Ellis, R., Jr., J. F. Davis, and D. L. Thurlow. 1964. Zinc availability in calcareous Michigan soils as influenced by phosphorus level and temperature. Soil Sci. Soc. Amer. Proc. 28:83-86.

Engler, R. M. 1969. The effects of applications of zinc on the yield and the chemical composition of corn, cotton, rice, and soybeans, grown on selected soils in Louisiana. M. S. Thesis. Louisiana State University, Baton Rouge, Louisiana.

Epstein, E., and P. R. Stout. 1951. The micronutrient cations iron, manganese, zinc, and copper: Their uptake by plants from the adsorbed state. Soil Sci. 72:47-66.

Gall, O. E., and R. M. Barnette. 1940. Toxic limits of replaceable zinc to corn and cowpeas grown on three Florida soils. J. Amer. Soc. Agron. 32:23-32.

Ganiron, R. D., D. C. Adriano, G. M. Paulsen, and L. S. Murphy. 1969. Effects of phosphorus carriers and zinc sources on Phosphorus-zinc interactions in corn. Soil Sci. Soc. Amer. Proc. 33:306-309.

International Rice Research Institute. 1969. Annual Report. The International Rice Research Institute, Los Banos, Laguna, Philippines. 1970.

International Rice Research Institute. 1970. Annual Report. The International Rice Research Institute, Los Banos, Laguna, Philippines. 1971.

Ishizuka, Y., and T. Ando. 1968. Interaction between manganese and zinc in growth of rice plants. Soil Sci. Pl. Nutr. 14:201-206.

Jackson, M. L. 1958. Soil chemical analysis. Prentice-Hall Inc., Englewood Cliffs, N. J.

Jones, L. P. H. 1956. The effect of liming a neutral soil on the uptake of manganese by plants. Plant Soil 8:301-314.

Kanehiro, Y., and G. D. Sherman. 1967. Distribution of total and 0.1 N hydrochloric acid-extractable zinc in Hawiian soil profiles. Soil Sci. Soc. Amer. Proc. 31:394-399.

Khan, D. H. 1969. Response of sweet corn and rice to phosphorus, zinc, and calcium carbonate on acid Glenview soil of California. Soil Sci. 108:424-428.

Kline, C. H. 1965. The need for zinc. Pub. Amer. Zinc Inst. New York, N. Y.

Leeper, G. W. 1970. Six trace elements in soils. Melbourne University Press, Melbourne, Australia.

Lingle, J. C., L. O. Tiffin, and J. C. Brown. 1963. Iron uptake-transport of soybeans as influenced by other cations. Plant Physiol. 38:71-76.

Lott, W. L. 1938. The relation of hydrogen ion concentration to the availability of zinc in the soil. Soil Sci. Soc. Amer. Proc. 3:115-121.

Maas, E. V., D. P. Moore, and B. J. Mason. 1968. Manganese absorption by excised barley roots. Plant Physiol. 43:527-530.

Martens, D. C., and G. Chesters. 1967. Comparison of chemical tests for estimation of the availability of zinc. J. Sci. Fd. Agr. 18: 187-193.

Martin, W. E., J. G. McLean, and J. Quick. 1965. Effect of temperature on the occurrence of phosphorus induced zinc deficiency. Soil Sci. Soc. Amer. Proc. 29:411-413.

Melton, J. R., B. G. Ellis, and E. C. Doll. 1970. Zinc, phosphorus, and lime interaction with yield and zinc uptake by Phaseolus vulgaris. Soil Sci. Soc. Amer. Proc. 34:91-93.

Millikan, C. R. 1942. Symptoms of zinc deficiency in wheat and flax. J. Australian Inst. Agr. Sci. 7:33-35.

Mortensen, J. R. 1963. Complexing of metals by soil organic matter. Soil Sci. Soc. Amer. Proc. 27:179-183.

Navrot, J., and S. Ravikovitch. 1969. Zinc availability in calcareous soil. 3. The level and properties of calcium in soils and its influence on zinc availability. Soil Sci. 108:30-37.

Pauli, A. W., R. Ellis, Jr., and H. Moses. 1968. Zinc uptake and translocation as influenced by phosphorus and calcium carbonate. Agron. J. 60:394-396.

Paulsen, G. M., and O. A. Rotini. 1968. Phosphorus-zinc interaction in two soybean varieties differing in sensitivity to phosphorus nutrition. Soil Sci. Soc. Amer. Proc. 32:73-76.

Ponnamperuma, F. M. 1964. Dynamic aspects of flooded soils and the nutrition of the rice plant. p. 295-328. In The mineral nutrition of the rice plant. John Hopkins Press, Baltimore, Maryland.

Randhawa, N. S., and F. E. Broadbent. 1965. Soil organic matter-metal complexes: 6. Stability constants of zinc-humic acid complexes at different pH values. Soil Sci. 99:362-366.

Rogers, L. H., and Chik-hwa-Wu. 1948. Zinc uptake by oats as influenced by application of lime and phosphorus. Agron. J. 40:563-566.

Rosell, R. A., and A. Ulrich. 1964. Critical zinc concentrations and leaf minerals of sugar beet plants. Soil Sci. 97:152-167.

Savant, N. K., and R. Ellis, Jr. 1964. Changes in redox potential and phosphorus availability in submerged soil. Soil Sci. 98:388-394.

Schmid, W. E., H. P. Haag, and E. Epstein. 1965. Absorption of zinc by excised barley roots. Physiol. Plant. 18:860-869.

Seatz, L. F. 1960. Zinc availability and uptake by plants as affected by the calcium and magnesium saturation and phosphorus content of the soil. 7th. Int. Con. Soil Sci. 11:36.

Seatz, L. F., and J. J. Jurinak. 1957. Zinc and soil fertility. p. 115-121. In Soils. Yearbook Agr. (US Dep. Agr.). US Government Printing Office, Washington, D. C.

Seatz, L. F., A. J. Sterges, and J. C. Kramer. 1959. Crop response to zinc fertilization as influenced by lime and phosphorus application. Agron. J. 51:457-459.

Sedberry, J. E., F. J. Peterson, Emmett Wilson, A. L. Nugent, R. M. Engler and R. H. Brupbacher. 1971. Effects of zinc and other elements on the yield of rice and nutrient content of rice plants. La. Agr. Exp. Sta. Bull. 653.

Senewiratne, S. T., and D. S. Mikkelsen. 1961. Physiological factors limiting growth and yield of Oryza sativa under unflooded conditions. Plant Soil. 14:127-146.

Shapiro, R. E. 1958. Effect of flooding on availability of phosphorus and nitrogen. Soil Sci. 85:190-197.

Sharma, K. C., B. A. Krantz, A. L. Brown, and J. Quick. 1968. Interaction of zinc and phosphorus with soil temperature in rice. Agron. J. 60:652-655.

Shaw, E., and L. A. Dean. 1952. Use of dithizone as an extractant to estimate the zinc nutrient status of soils. Soil Sci. 73:341-347.

Shaw, E., R. G. Menzel, and L. A. Dean. 1954. Plant uptake of zinc 65 from soils and fertilizers in the greenhouse. Soil Sci. 77:205-214.

Sommer, A. L., and C. B. Lipman. 1926. Evidence of the indispensable nature of zinc and boron for higher green plants. Plant Physiol. 1:231-248.

Stukenholtz, D. D., R. J. Olsen, G. Gogan, and R. I. Olsen. 1966. On the mechanism of phosphorus-zinc interaction in corn nutrition. Soil Sci. Soc. Amer. Proc. 30:759-763.

Tanaka, A., R. Loe, and S. A. Navasero. 1966. Some mechanism involved in the development of iron toxicity symptoms in the rice plant. Soil Sci. Pl. Nutr. 12:32-38.

Thorne, W. 1957. Zinc deficiency and its control. Advan. Agron. 10: 31-65.

Tiffin, L. O. 1967. Translocation of manganese, iron, cobalt, and zinc in tomato. Plant Physiol. 42:1427-1432.

Toth, S. J., A. L. Prince, A. Wallace, and D. S. Mikkelsen. 1948. Rapid quantitative determination of eight elements in plant tissue by a systematic procedure involving a flamephotometer. Soil Sci. 66:459-466.

Tucker, T. C., and L. T. Kurtz. 1955. A comparison of several methods with the bioassay procedure for extracting zinc from soils. Soil Sci. Sci. Soc. Amer. Proc. 19:477-481.

Viets, F. G., Jr., L. C. Boawn, C. L. Crawford. 1957. The effect of nitrogen and types of nitrogen carrier on plant uptake of indigenous and applied zinc. Soil Sci. Soc. Amer. Proc. 21:197-201.

Viets, F. G., Jr., L. C. Boawn, C. L. Crawford, and C. E. Nelson. 1953. Zinc deficiency of corn in Washington on neutral and alkaline soils. Agron. J. 45:559-565.

Vlamis, J., and R. A. Davis. 1944. Effects of oxygen tension on certain physiological responses of rice, barley, and tomato. Plant Physiol. 19:33-51.

Walkley, A. and I. A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37:629-672.

Ward, R. C., E. J. Langin, R. A. Olsen, and H. F. Rhoades. 1962. Factors responsible for poor response of corn and grain sorghum to phosphorus fertilization: II. Lime and phosphorus placement effects on P-Zn relations. Soil Sci. Soc. Amer. Proc. 26:574-578.

Warnock, R. C. 1970. Micronutrient uptake and mobility within corn plants in relation to phosphorus induced zinc deficiency. Soil Sci. Soc. Amer. Proc. 34:765-769.

Wear, J. I. 1956. Effect of soil pH and calcium on the uptake of zinc by plants. Soil Sci. 81:311-315.

Wear, J. I. 1959. Zinc deficiency, a common disorder of corn. Highlights of Agr. Res. Alabama Polytechnic Institute.

Wear, J. I., and A. L. Sommer. 1948. Acid-extractable zinc of soils in relation to the occurrence of zinc deficiency symptoms of corn: a method of analysis. Soil Sci. Soc. Amer. Proc. 12:143-144.

Yamasaki, T. 1964. The role of the micronutrients. p. 107-122. In The mineral nutrition of the rice plant. John Hopkins Press, Baltimore, Maryland.

Yoshida, S., D. A. Forno, J. H. Cock, and K. A. Gomez. 1972. Laboratory manual for physiological studies of rice. 2nd. Ed. International Rice Research Institute, Los Nanos, Laguna, Philippines.

Yoshida, S., and A. Tanaka. 1969. Zinc deficiency of the rice plant in calcareous soils. Soil Sci. Pl. Nutr. 15:75-80.

VITA

Harold Joseph Aymond was born May 19, 1941, in Evergreen, Avoyelles Parish, Louisiana. He graduated from Bunkie High School in 1959.

He attended the University of Southwestern Louisiana and received his Bachelor of Science degree in agronomy in January 1964. He then entered Naval Officer Candidate School in Newport, Rhode Island and was commissioned an Ensign in the United States Naval Reserve in September 1964. After receiving his commission, he was married to the former Carolyn Ann Billeaud of Lafayette, Louisiana. He served a three year tour of active duty in the Navy and was honorably discharged in August 1967.

He began graduate study at Louisiana State University in September 1967 after being granted a Graduate Assistantship in the Department of Agronomy. He received his Master of Science degree in January 1970. He is presently a candidate for the degree of Doctor of Philosophy in the Department of Agronomy.